Increasing use of composites in

Aircraft, Automotive and Civil Engineering

requires a better understanding of its

behaviour under static, cyclic and dynamic loading.

... therefore, reliable material models and properties are required !

Ralf Cuntze: *Retired engineer* and *hobby material modeller*

Formerly: MAN-Technologie AG Augsburg, Head of Main Department 'Structural and Thermal-Analysis'
Now: linked to Carbon Composites e.V. (CCeV) Augsburg and IHK-Schwaben, Bayern Innovativ

- 1959 - 1964 Study of Civil Engineering at Hannover ('stress man')
- 1968 Dr.-Ing. in Structural Dynamics
- 1978 Dr.-Ing. habil. in Mechanics of ***Lightweight Structures***
- 1980 - 2003 Lecturer at 'Universität der Bundeswehr' München on fracture mechanics and ***lightweight structures*** from Fiber Reinforced Plastics (FRP)

<u>Professional career:</u>

1968 - 1970 DLR (German aerospace center: finite element analysis programming)

1970 - 2004 MAN-Technologie, Munich/Augsburg: involved in the *Development of* :

- ARIANE 1-5 Launcher family: Components of central stage + Boosters, high pressure vessels, etc.
- Windenergy rotors (Growian Ø103m, WKA 60, Aeroman). ***Since 1970 in Carbon Comp. business***
- Satellite components, Space Antennas; FRP light weight structures, IRAM antenna, SOFIA telescope (in Boeing 747); Automated Transfer Vehicles (ATV1 Jules Verne) + Crew Rescue Vehicle CRV (for ISS) + NASA X38 Demonstrator space plane
- CMC body flap for Crew Rescue Vehicle (2002), Spacelab mission D1 (1985): material experiments,
- Apogee solid propellant motor cases MAGE and IRIS, water-tanks for AIRBUS
- Heat exchanger for gas cooled Solartower GAST(20 MW) and Solarfield constructions (Almeria)
- Gasultra-Centrifuge, Fly wheels (for ship "Trans Swartow", MAN-Buses), Diesel engine parts in metal and in monolithic ceramics for trucks, Structural calculations for MAN buses
- Fusion reactor WENDELSTEIN VII: toroidal ring chamber.

Material applications in the range: 20 K through 2000 K (FRP, CMC, metals, concrete).

<u>Co-author and Convenor of various Handbooks and Working Groups</u>

- IASB - German Aircraft Structural Handbook HSB: since 1972 author and co-author of a large number of design sheets. Co-author of the HSB-Handbook's 'transfer' team into English
- VDI 2014 Guideline "Development of Fibre Reinforced Plastic Compon." (co-author, convenor), VDI-WG 4.3 "Reliability of Structural Components" (1980ies, WG member)
- ESA/ESTEC, since 1978: Structural Requirements Standards, co-author in the 3 working groups: Structural Analysis, High Pressure Vessels (metal and composites), Safety Factors; Contributor to Handbooks: PSS and follower Structural Materials Handbook SMH; Buckling Handbook (first convenor, contributor to several chapters); ECSS (European Cooperation for Space Standardization)
- was involved in EU projects (BRITE, BRITE-EURAM), and BMFT and BMBF research projects.

<u>Miscellaneous</u>

- Surveyor/advisor (since 1980) for German Ministry BMFT + BMBF on R&D Material Programmes (MaTech, MatFo, LuFo, German Material Modelling competence centres). Advisor to EU-project MAAXIMUS (Airbus Toulouse: On improving Aircraft sizing)
- Advisor for German Research Foundation DFG (SFBs, SPPs on modelling structural textiles)
- Originator of the (never funded) successful Failure Mode Concept (FMC), a general invariant-based foundation for the derivation of failure mode-linked *strength failure conditions* for isotropic, transversely-isotropic (UD), and orthotropic (fabrics) materials applicable for FRP, CMC, metals, concrete, etc. Winner of the World-Wide-Failure-Exercise-I on "UD composites strength failure theories" (WWFE-I, bi-axial stress states). Now, top-ranked in WWFE-II on "UD, tri-axial stress states" considering hydrostatic pressures > 700 MPa
- Numerous 'single-author' publications in different structural fields
- Founder (2010) and co-worker of the working group 'Fatigue of Composites' (only group, world-wide) of all respective German universities. Founder and Leader of the Carbon Composites working groups 'Engineering' (2009) and 'Fiber-Reinforcement in Civil Engineering' (2011). Member of the world-wide NAFEMS Composite Working Group

1964: **Diplom** ***Statiker***

1968: **Dr.-Ing.** ***Strukturdynamik***

1978: **Dr.-Ing. habil.** ***Mechanik des Leichtbaus***

1968- 1970: frühere DLR ***Finite Element Analyse***

1970-2004: MAN-Technologie (GUZ, Raumfahrt, Wind- und Sonnenenergie, …)

1980-2002: Dozent an der Universität der Bundeswehr

jetzt: Ingenieur, Unruheständler + Simulant

Convenor of CCeV working groups : '(mechanical) Engineering and 'Modelling Fiber Reinforcement in Civil Engineering'

Theoretical works in the areas:

Finite Element Analysis, Structural and Rotor dynamics,

Structural reliability and Development policy,

Strength failure modes and hypotheses (isotropic + composites),

Composites fatigue, Damaging mechanics and Fracture mechanics.

Which Design Verifications are mandatory in Structural Design ?

Analysis of *Design Loads, Dimensioning Load Cases* ← **standards**

Thermal analysis

Hygro-thermal mechanical Stress and Strain analysis
(input: average physical design data)

Damage tolerance, crash, and fatigue life demonstration

after initial failure
onset of cracks,
delamination growth

Stiffness, Strain, Deformation demonstration

Strength demonstration

Stability demonstration

before initial failure

TASK:

Structural Resistances *must be demonstrated* by
a *positive* **Margin of Safety *(MoS)*** *or* ***RF >1,***
to proof ***Design Verification***
for achieving **Structural Integrity**

Verification Levels of the Structural Part with

- Local Stress at a critical material ‘point‘: **continuumsmechanics, strength criteria**
  verification by a *basic strength* or a *multi-axial failure stress state*
  Applied stresses are local stresses

- Stress concentration at a notch (stress peak at a joint): **notch mechanics**
  verification by a *notch strength* *(usually Neuber-like, Nuismer, etc..)*
  ‘Far‘-field stresses are acting and are not directly used in the notch strength analysis

- Stress intensity (delamination = crack): **fracture mechanics**
  verification by a *fracture toughness (energy –related)*
  Applied stresses are ‘far‘-field stresses.(far from the crack-tip)

… gilt statisch wie zyklisch

CONSTRAINTS in Design Development Process : *Cost and Time Reduction*

Industry looks for robust & reliable analysis procedures
in order to replace the expensive 'Make and Test Method'
as far as reasonable.

Virtual tests *shall reduce the amount of* physical tests.

In this context:

Structural Design Development

can be only effective and offer high fidelity

if

qualified analysis tools and necessary test data input are available

for Design Dimensioning and for Manufacturing as well.

a Strength Failure Condition (SFC) is for instance such an Analysis Tool

The presentation plus further literature may be downloaded from http://www.carbon-composites.eu/leistungsspektrum/fachinformationen/fachinformation-2

Material Properties and Model Parameters, necessary for the Analysis of Static, Cyclic, and Dynamic Stress States

- embedded in Structural Design Development

Short Presentation of CCeV + personal activities

1. **Structural Development, Design Requirements, and Design Verifications**
2. **Dimensioning Load cases, Safety Concept and Design Factors of Safety**
3. **Modelling of Composites (elasticity, strength)**
4. **Material Strength Failure Conditions (SFC)**
5. **Application of SFCs to Some Materials**
6. **Lifetime Prediction**
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8. **Model Parameters**
9. **Standardized Material Test Methods**
10. **Structural Testing, NDI, Damage Tolerance**
11. **Structural Verification, Reserve Factor**

(matrix, fiber, interphase, composite)

Prof. Dr.-Ing. habil. Ralf Cuntze VDI
retired from MAN-Technologie, now linked to Carbon Composites e.V. (CCeV), Augsburg
presents results of a time-consuming 'Hobby'

Carbon Composites eV (CCeV) =

Association of companies and research institutions,

covering the entire value chain of

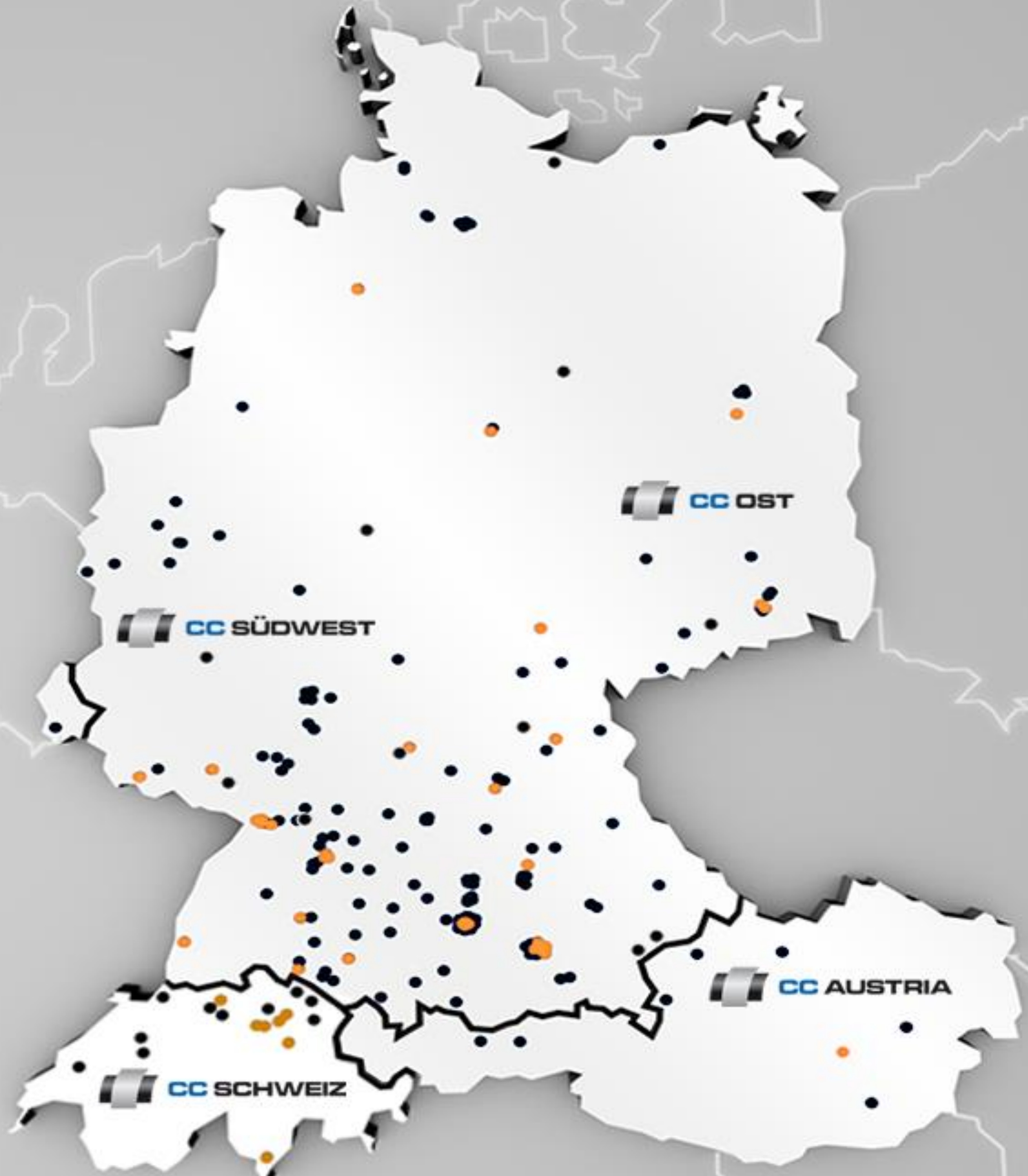
high-performance fiber reinforced composites

in Germany, Austria and Switzerland (DACH).

Focus : Promotion of Carbon Fiber Technology

Serving as competence network :

- Support and linking collaboration between science, small and large companies
- Transfer of available know-how and existing competences
- Organized as an association
- Founded in 2007, based in Augsburg
- Financed by membership fees
- The leading Carbon Composites Network in the German-speaking world !



CARBON COMPOSITES

Regional Departments

CC OST	2012
CC SÜDWEST	2012
CC SCHWEIZ	2012
CC AUSTRIA	2012

Cluster Department

M·A·I CARBON	2012

DACH Area: Specialist Departments

CERAMIC COMPOSITES	2008
CC TUDALIT	2012

Together with TUDALIT e.V.

● = Research Institution ● = Industry

Distribution of the - at present - 275 members

Sectors

System companies
- Aerospace
- Automotive engineering
- Civil engineering
- Medical technology
- Energy technology
- etc.

Supplier companies
- Fibres, semi-finished products, ancillary materials, coatings
- Assemblies, components
- Tooling machines, processing systems, equipment, plants
- Software and services (e.g. engineering, factory planning)


Bildnachweis: Airbus, ALIEN-Projektteam, KUKA

CCeV‘s activities

Technical working groups - fiber-reinforced plastics

… Material

- AG Materialien
- AG Garne und Textilien
- AG Thermoplaste
- AG Biocomposites
- AG Faserbewehrte Kunststoffe im Bauwesen

… Design & Characterisation

- AG Engineering
- UAG Composite Fatigue
- AG Multi-Material-Design
- AG Klebetechnik
- AG Smart Structures
- AG Werkstoff- und Bauteileprüfung
- AG Werkstoffmod./Berechn. im Bauwesen

… Process

- AG Herstellverfahren
- AG Automatisierung
- UAG Herstellprozess-Simulation
- AG RTM Next Steps
- AG Werkzeug- und Formenbau

… Finishing

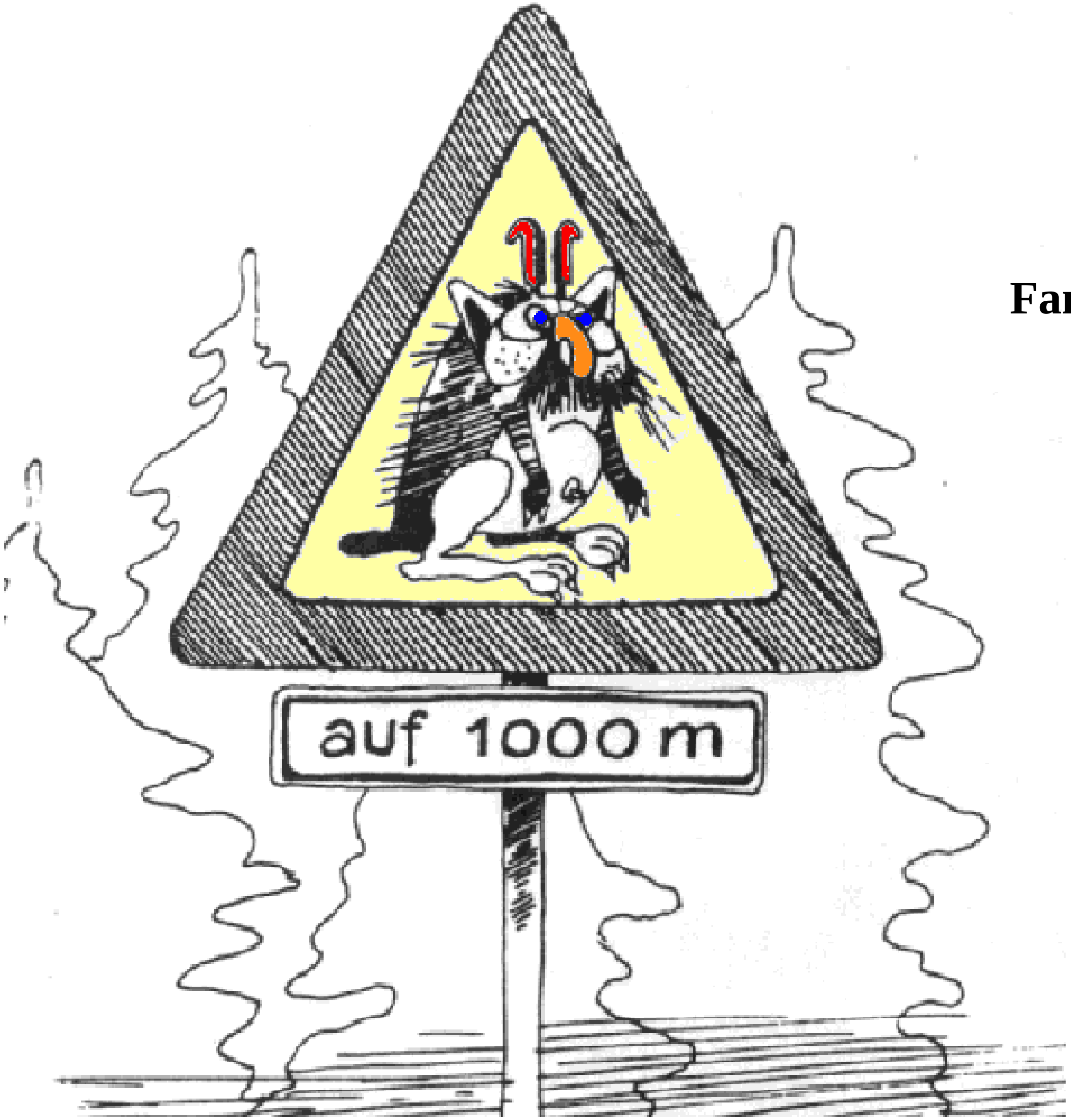
- AG Bearbeitung
- UAG Absaugtechniken & Schutzmaßnahmen
- AG Oberflächenbeh., Beschichtung, Lackierung
- UAG Roadmap OBL

… Cross Section Issues

- AG Kostenschätzung
- AG Normung und Standardisierung
- AG Roadmap CFK
- AG Umweltaspekte

The Competence Network Carbon Composites e.V. (CCeV

Why did we perform this in Bavaria, first ? Experience ? ..



Yes,

the Wolperdinger.

Famous Composite-Construction of the High-Tec Country *Freistaat* Bayern

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9. **Standardized Material Test Methods** **Kollege**
10. **Structural Testing, NDI, Damage Tolerance**
11. **Structural Verification, Margin of Safety, Reserve Factor**

Development Phases and Associated Topics

Phase		DESIGN	Design Analysis	Test
1	concept	conceptual	sizing	
2	design development	preliminary	dimensioning	design development tests
3		critical (final)	analytical design verification	
4	qualification	accepted		experimental design verification
5	production			

certification of product

Development: Process phases from defining requirements until product delivery

Designing: Iterative process in the development of the structural component whereby various concepts are evolved and evaluated against a set of specified design requirements and constraints from manufacturing etc.

Design Verification: Process, whereby a structural design is comprehensively examined and qualification-tested to ensure that it will perform in the required way, before and during operational use.

Some Definitions

Safety Concept

Concept that implements structural reliability (safety is a wrong term) in design

(design) Factor of Safety (FoS)

Factor by which design limit loads (DLL) are multiplied in order to account for uncertainties of the verification methods, uncertainties in manufacturing process and material properties

Failure Modes (material, structural and others)

Yield initiation, fracture, degradation, excessive wear, fibre fracture, inter fibre fracture, delamination, instability, or any other phenomenon resulting in an inability to sustain environmental 'loadings' (not only loads)

Service life of a Structural Component

Starts with the manufacture of the structure and continues through all acceptance testing, handling, storage, transportation, operation, repair, re-testing, re-use

What is a Material ?

= homogenized (smeared) model of the envisaged complex material which might be a material combination

What is Failure?

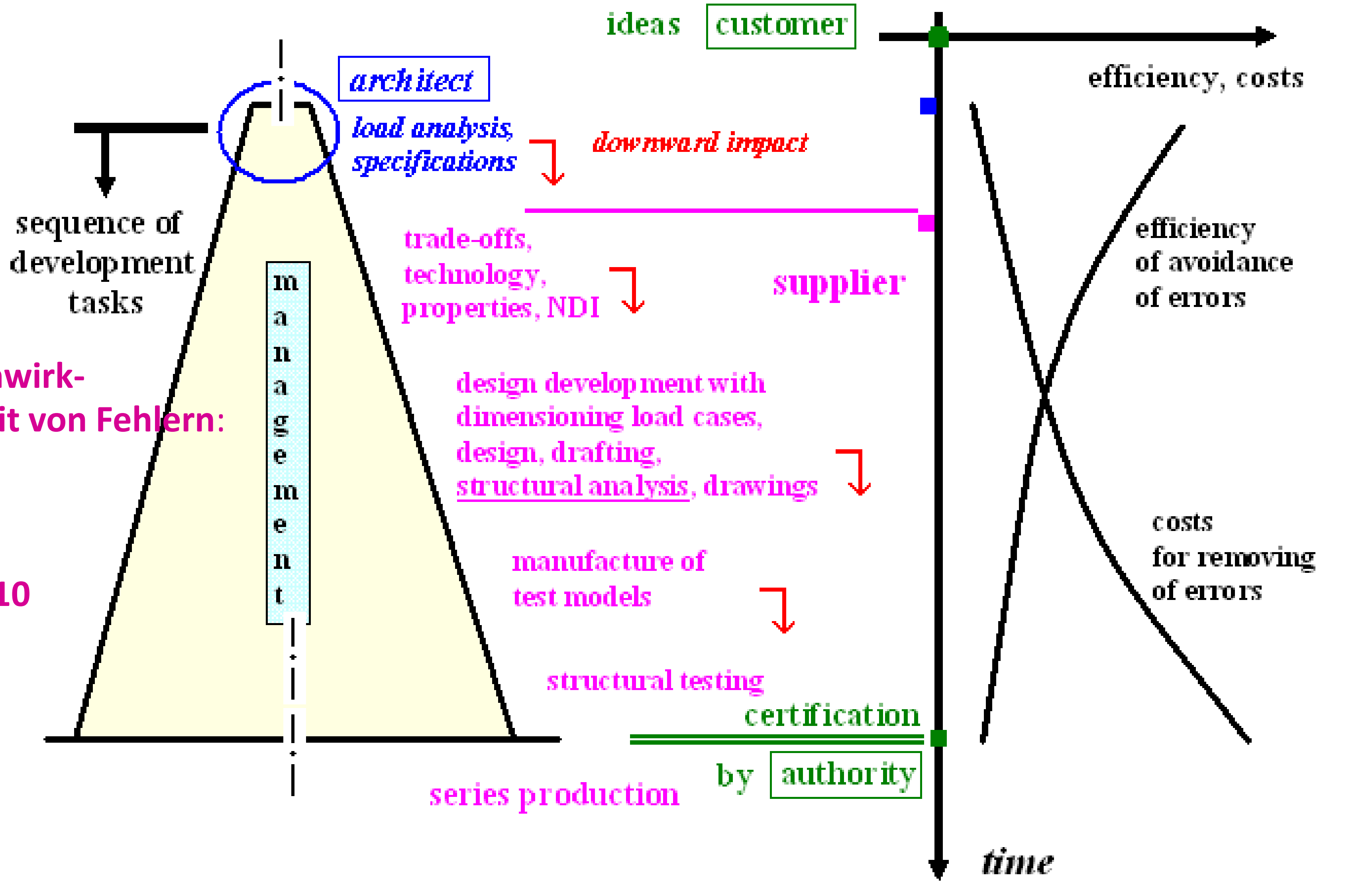
If the structural part does not fulfil its functional requirements (FF = fiber failure, IFF = inter-fiber-failure (matrix failure, leakage, deformation limit, delamination size limit, …)

What is Fatigue ?

= process, that degrades material properties

Cost Penalty by Mistakes during Design Development Process Phases

Compromise: Cost → Minimum, Quality → Maximum



Kostenwirk-samkeit von Fehlern:

10
x 10
x 10

Robust design helps to smooth out not-foreseen errors, to save cost & reduce troubles !

What does the stress engineer speak about ?

Material: homogenized macromechanical model of the envisaged solid consisting of different constituents

Failure: structural part does not fulfil its functional requirements such as onset of yielding, onset of brittle fracture, Fiber-Failure FF, Inter-Fiber-Failure IFF, leakage, deformation limit, delamination size limit, frequency bound

= project-fixed Limit State with F = Limit State Function

Failure Criterion: F >=< 1 , Failure Condition : F = 1= 100%

F = mathematical formulation of the failure surface (body)

Failure Theory: general tool to predict failure of a structural part,

captures (1) Failure Conditions, (2) Non-linear Stress-strain Curves of a material as input, (3) Non-linear Coding for structural analysis

Strength Failure Condition (SFC) = subset of a strength failure theory

tool for the assessment of a

'multi-axial failure stress state ' in a critical location of the material.

Industrial Requirements for Improved Designing of Composite Parts

Static loading:

- Validated 3D strength failure conditions for isotropic (foam), transversely-isotropic UD materials, and orthotropic materials (e.g. textiles) to determine ‘Onset of fracture‘ and ‘Final fracture‘
- Standardisation of material test procedures, test specimens, test rigs, and test data evaluation for the structural analysis input
- Consideration of manufacturing imperfections (tolerance width of uncertain design variables) in order to achieve a production cost minimum by „Design to Imperfections“ includes defects

Cyclic (dynamic) loading : fatigue

- Development of practical, physically-based lifetime-prediction methods
- Generation of S-N curve test data for the verification of prediction models
- Delamination growth models: for duroplastic and thermoplastic matrices
- Consideration of media, temperature, creeping, aging
- Provision of more damping because parts become more monolithic.

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for visualization some examples

Consideration of Load Assumptions:

z.B.

- Prüfvorschriften,
- Betriebs- und Mißbrauchslasten, Crash
- Fahrbetriebsmessung, Streckenmischung
- 1%-Fahrer, Lastkollektiv,
- Sicherheitsklasse des Bauteils,
- Unterschiede für : Pkw, LKW, Anhänger mit
  Kupplung, Dachlast, Motorrad

Load Analysis

<u>Main task is:</u>

Establishment of load events the structure is likely to experience (= load history)

Includes the estimation of all external + internal loadings of the structural component :

- thermal,
- mechanical (static, cyclic, and dynamic) and
- acoustical environment as well as of the
- corresponding lifetime requirements (duration, number of cycles)

Loadings are specified by
a Technical Specification from the customer, or an authority or
a common standard (EN, DIN, Betonkalender, ...)

GROWIAN 1979, under-estimation of load peaks

<u>Result:</u>

Set of Combinations of Loadings termed *Load Cases*,
including the design driving *Dimensioning Load Cases*

Involves a Worst case scenario wrt. combinations of loadings, temperature and moisture, and undetected damage.

Dimensioning Load Cases

From the numerous *Load Cases*

the design driving ***Dimensioning Load Cases (DimLC)*** are to be sorted out:

- for ductile behaviour the : Yielding-related Load Cases,
- for brittle behaviour the : Ultimate-related Load Cases (for CFRP).

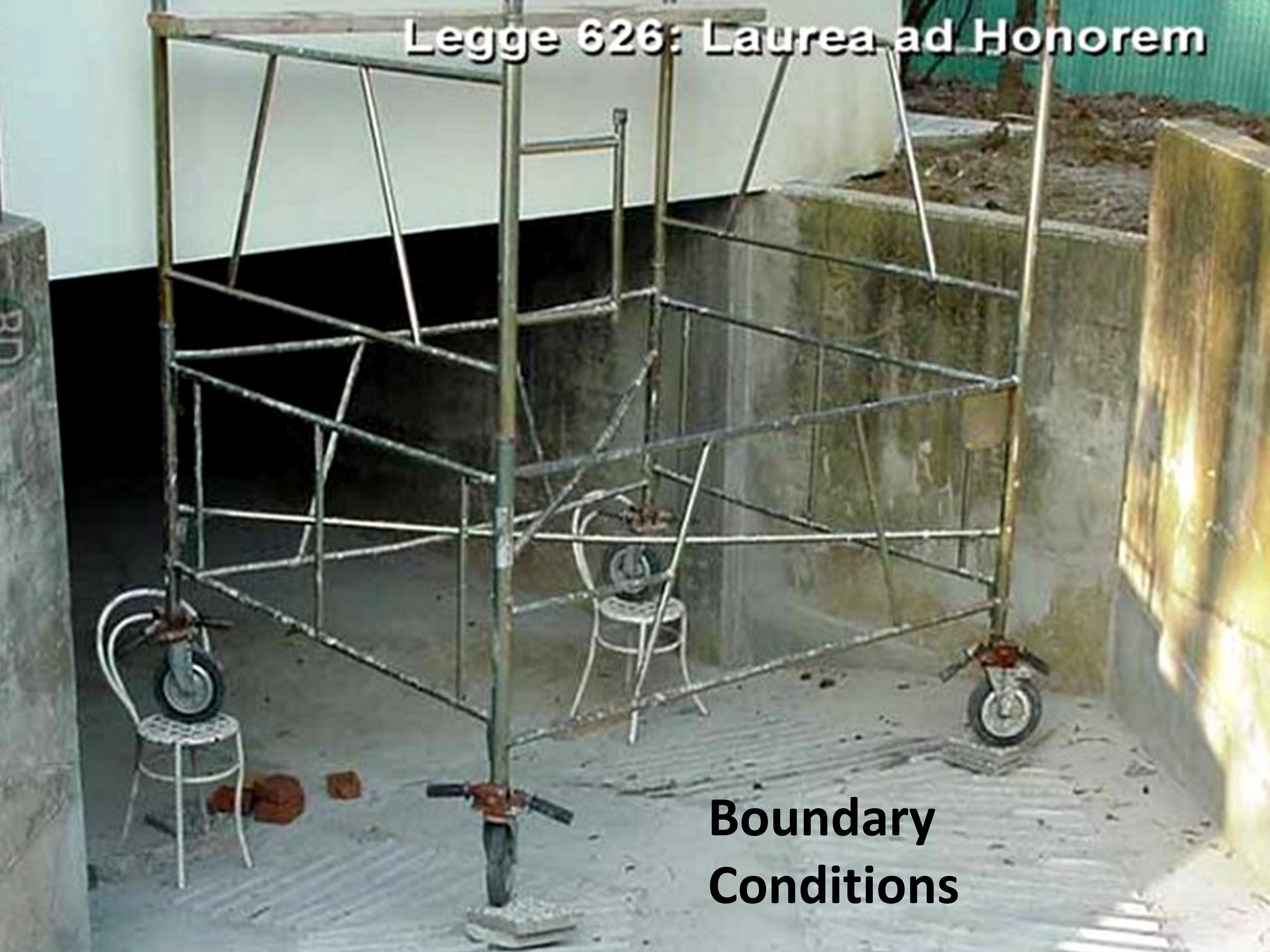
A minimum set of DimLCs is searched in order to:

- support fast engineering decisions in cases of 'input' changes

- avoid analysis and analysis data evaluation overkill and

- better understand structural behaviour (as hidden aspect).

Which *LC* is a *DimLC* can be often firstly recognized after the analysis of the conceptual design !


Legge 626: Laurea ad Honorem
Boundary Conditions

Example for a Factors of Safety (FOS) Table

New Standard: prepared 10 years ago.

shows up higher risk than usual

Structure type / sizing case	FOSY $j_{p0.2}$	FOSU j_{ult}	FOSY *for verification 'by analysis only'*	FOSU *for verification 'by analysis only'*	*Design Factor*	FOSY $j_{p0.2}$	FOSU j_{ult}	j_{proof}	j_{burst}
	external loadings incl. extern press.					internal pressure			
Metallic structures	1.1	1.25	1.25	1.5		1.0	1.0	1.2	1.5
FRP structures (uniform material)	?	1.25	-	1.5		1.0	1.0	1.?	1.5
FRP structures (discontinuities)	-	1.25	-	1.5	1.2				
Sandwich struct.: - Face wrinkling - Intracell buckl. - Honeycomb shear	-	1.25 1.25 1.25	-	1.5 1.5 1.5					
Glass/Ceramic structures	-	2.5	-	5.0					
Buckling	-	1.5	-	?					

(ECSS-E-30-10, spacecraft)

Term $j_{p0.2}$ does not so much fit to actual (relatively brittle) composites!

Note the Difference: *Test Data Mapping and Design Verification*

- Validation of SFCs with Failure Test Data by

  mapping their course by an average Failure Curve (surface)

For each distinct Load Case with its single Failure Modes a RF must be computed:

- Delivery of a reliable Design Verification by

  calculation of a Margin of Safety or a (load) Reserve Factor

$$MoS > 0 \quad oder \quad RF = MoS + 1 > 1$$

on basis of a statistically reduced failure curve (surface) .

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Features of Modeling laminated, high-performance Composites

** Lamina-based, sub-laminate-based (e.g. for non-crimp fabrics) or laminate-based !*

* Is performed, if applicable, *according to the distinct symmetry of envisaged material*

* For the chosen material model, if material symmetry-based, *the number of the measured inherent Strengths and Elasticity Properties is the same as the observed number of Failure Modes !!* Test costs reduction

* Achievement of equivalent stresses for each failure mode to obtain information where the lamina design screw must be turned !

Lesson-Learned: As far as the failure mode or failure mechanism remains,

Static Strength Criteria can be used for Cyclic Loading, too !

Very essential !

Modeling: ‘Simple‘ UD material = Lamina (ply)

1 Lamina = Layer of a Laminate, e.g. UD-laminas = “Bricks“

- *Homogenisation of a solid to a material brings benefits.*
- Then knowledge from Material Symmetry applicable : *number of required material properties is minimal, test-costs too*

UD-lamina, modeled a homogenised (‘smeared‘) material requires in

The Material Characterisation $f\,(T_{emp}, M_{oisture}, t_{ime}, etc.)$

Assumptions for UD Modelling and Mapping of Failure Stress data

- The UD-lamina is macroscopically homogeneous.

  It can be treated as a homogenized (‘smeared‘) material

  Homogenisation of a solid to a material brings benefits.

  Then Knowledge of Material Symmetry applicable : number of required material properties are minimal, test-costs too

1 Lamina (ply) = Layer of a Laminate, e.g. UD-laminas = “Bricks“

- The UD-lamina is transversely-isotropic:

On planes, parallel to the fiber direction it behaves orthotropic and on planes transverse to fiber direction isotropic (quasi-isotropic plane)

- Mapping: Uniform stress states are about the critical stress location !

Plenty combinations of different Constituents of polymeric Composites

Aramide

Carbon

Glass.

filament

Endless fibers

Long fibers

Short fibers.

interphase

Production Processes

matrix

Thermosets

Thermoplastics

Elastomers.

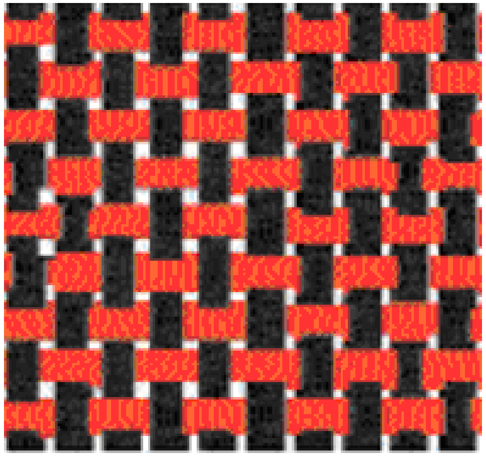
All these combinations

- need a different treatment and
- afford an associated understanding of its internal material behaviour.

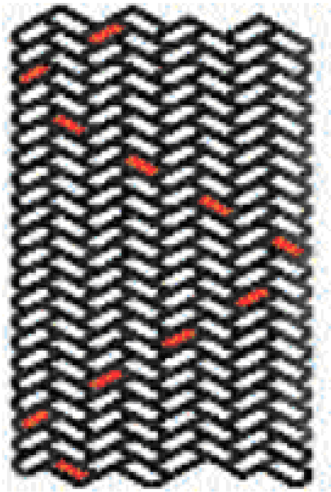
… and - coming up more and more – an increasing variety of 2D- and 3D-fabrics

Coming up: The Textile Challenge to achieve Certification

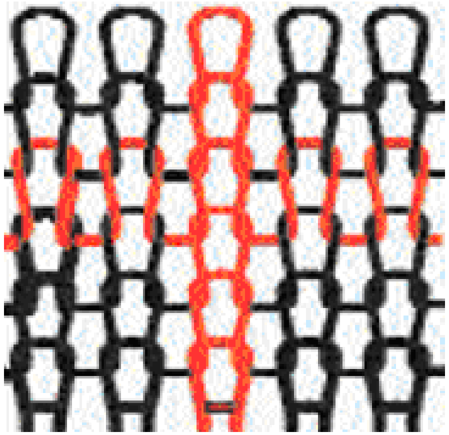
UD is much simpler !



plain weave

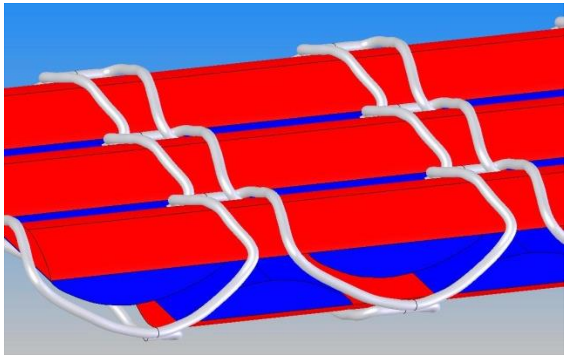


braid



weft knit

warp knit



non-crimp fabrics from UD-laminas for
high-performance applications

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Consequence for the poor Designer: *To ask*

Is there any Strength Failure Condition ("criterion")
he can apply with high fidelity?

Not at all !

Some well-known Developers which formulated isotropic 3D Strength Failure Conditions (SFCs)

Willam-Warnke, Ottosen etc.

Hencky-**Mises**-Huber

Richard von Mises
1883-1953
Mathematician

Eugenio Beltrami
1835-1900
Mathematician

Otto Mohr
1835-1918
Civil Engineer

Charles de Coulomb
1736-1806
Physician

'Onset of Yielding'

'Onset of Cracking'

Hence again, a civil engineer may proceed

State of the Art: <u>Static</u> Strength Analysis *of UD laminas*

Is represented best by the results of the *World-Wide-Failure-Exercises*

Organizer : *QinetiQ , UK* *(Hinton, Kaddour, Soden, Smith, Shuguang Li)*

Aim: *'Testing Predictive Failure Theories for*

Fiber–Reinforced Polymer Composites to the full !'

(was for the transversely-isotropic UD materials , only)

Method of the World-Wide-Failure-Exercises (since 1991**):**

Part A of a WWFE: ***Blind Predictions on basic strength data***

Part B of a WWFE: ***Comparison Theory-Test*** *with (reliable)*
<u>Uni-axial</u> 'Failure Stress Test Data' (= <u>basic strength)</u> and
Multi-axial 'Failure Stress Test Data'

(plain test specimens, no notch)

Global and Modal Strength Failure Conditions *General View*

Drucker-Prager, Tsai-Wu

1 Global *strength* failure condition : F ({σ}, {R}) = 1 (usual formulation)

Set of Modal strength failure conditions: F ({σ}, R^{mode}) = 1 (addressed in FMC)

Mises, Puck, Cuntze

Example: UD

vector of 6 stresses (general)

$$\{\sigma\} = (\sigma_1, \sigma_2, \sigma_3, \tau_{23}, \tau_{31}, \tau_{21})^T$$

vector of 5 strengths

$$\{R\} = (R_{\parallel}^t, R_{\parallel}^c, R_{\perp}^t, R_{\perp}^c, R_{\perp\parallel})^T$$

needs an Interaction of Failure Modes: performed by a

probabilistic-based 'rounding-off' approach (series failure system model)

directly delivering the (material) reserve factor in linear analysis

---

Note: In the quasi-isotropic plane of the UD material just 5 stresses are active:

$$\{\sigma\}_{principal}^{quasi\text{-}isotropic\ plane} = (\sigma_1, \sigma_2^p, \sigma_3^p, 0, \tau_{31}^p, \tau_{21}^p)^T$$

By-the-way: Experience with Failure Prediction prove

A Strength Failure Condition (SFC) is a necessary but not a sufficient condition to predict Strength Failure (example: thin-layer problem).

On top, an energy condition may be to fulfill.

Facts of so-called Modal SFCs

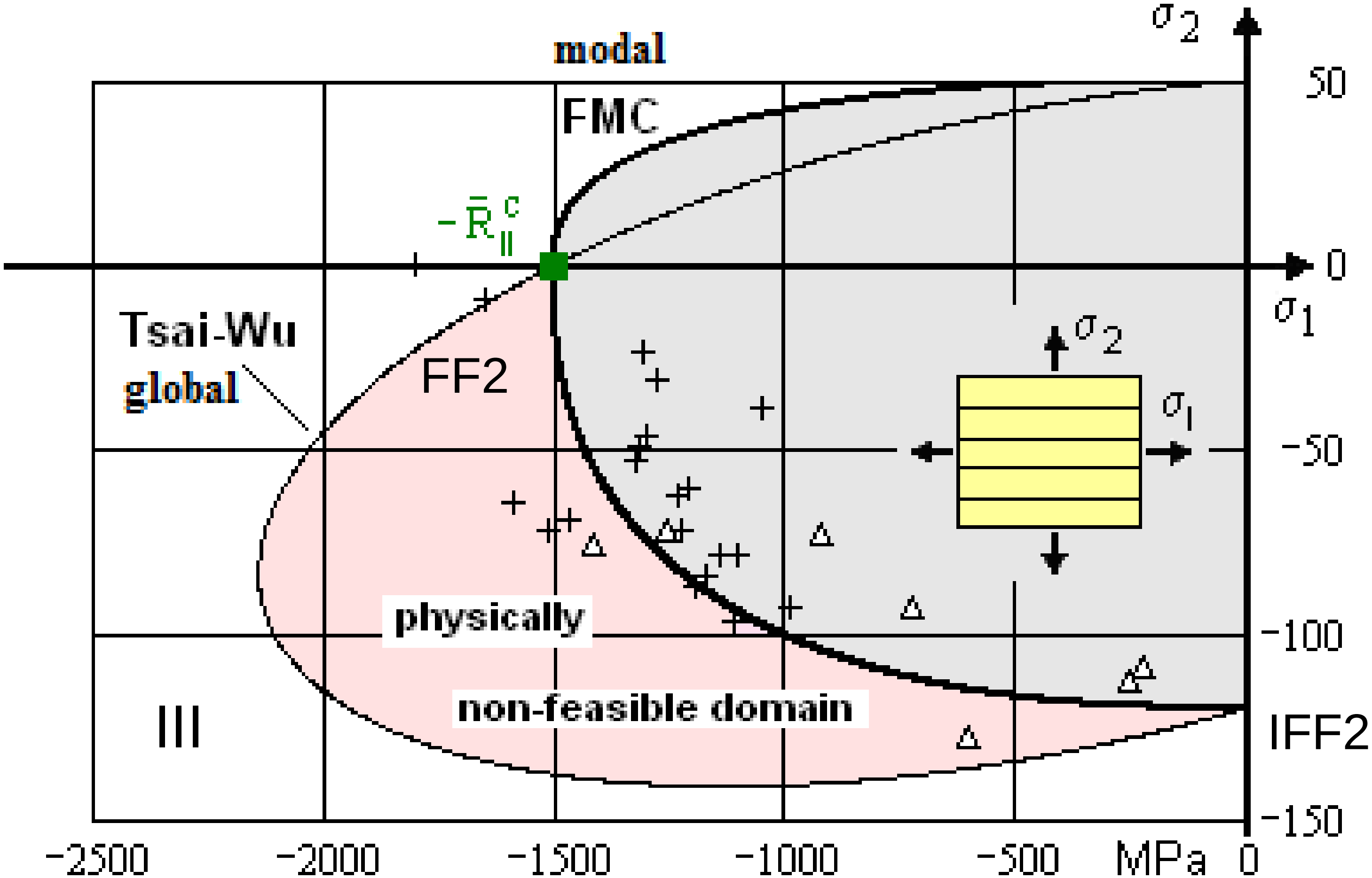
Modal SFCs (multi-suface domains)

- Describe one single failure mode in one single mathematical formulation (= one part of the failure surface)

  * determine all mode model parameters in the respective failure mode domain * capture a twofold acting failure mode separately, such as $\sigma_I = \sigma_{III}$ (isotropic) or $\sigma_2 = \sigma_3$ (transversely-isotropic UD material), mode-wise by the well-known Ansatz f (J_2, J_3)

- Re-calculation of the model parameters and of RF just in that failure mode domain where test data must be replaced.

Mapping in the 'Tsai-Wu non-feasible domain' (quadrant III)



$$\sigma_2(\breve{\sigma}_1 \equiv \sigma_1)$$

Data: courtesy IKV Aachen, Knops

Lesson Learnt: The modal FMC maps correctly, the *global* Tsai-Wu formulation predicts in quadrant III a non-feasible domain !

Test-observed Strength Failure Modes of Brittle behaving Isotropic Materials

Normal Fracture (NF) — no material element change before fracture

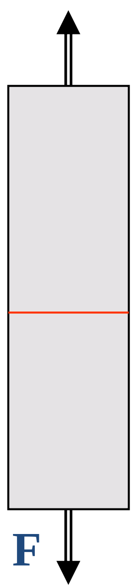
Shear Fracture Mode (SF) — shape change of material element

Crushing Fracture (CrF): — volumetric element change before fracture

*helpful knowledge for the later **choice of invariants***

if brittle: failure = fracture failure

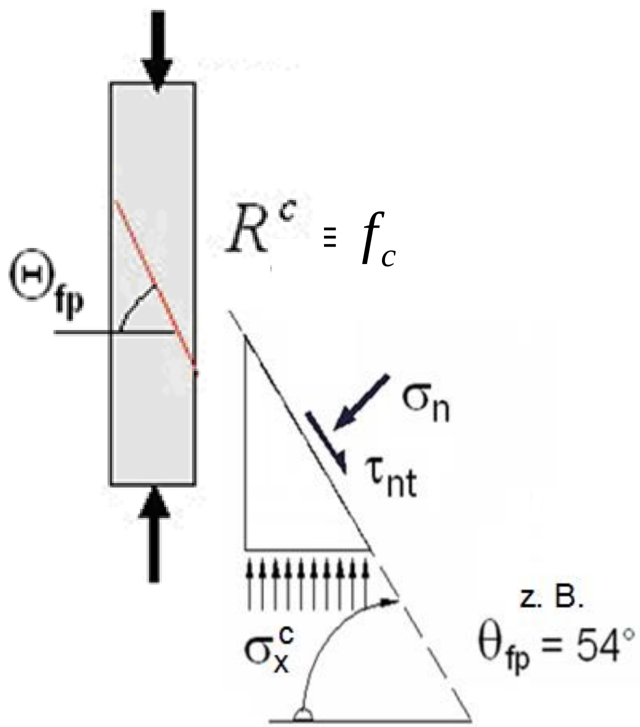
Tension



$$R^t = f_t$$

Compression

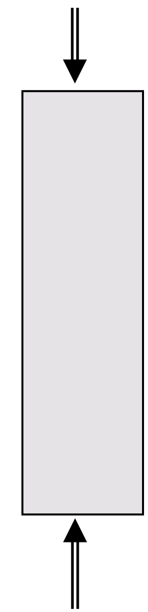
dense consistency



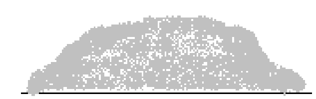
$$R^c \equiv f_c$$

fracture plane angle = measure for friction value

porous consistency



= decomposition of texture

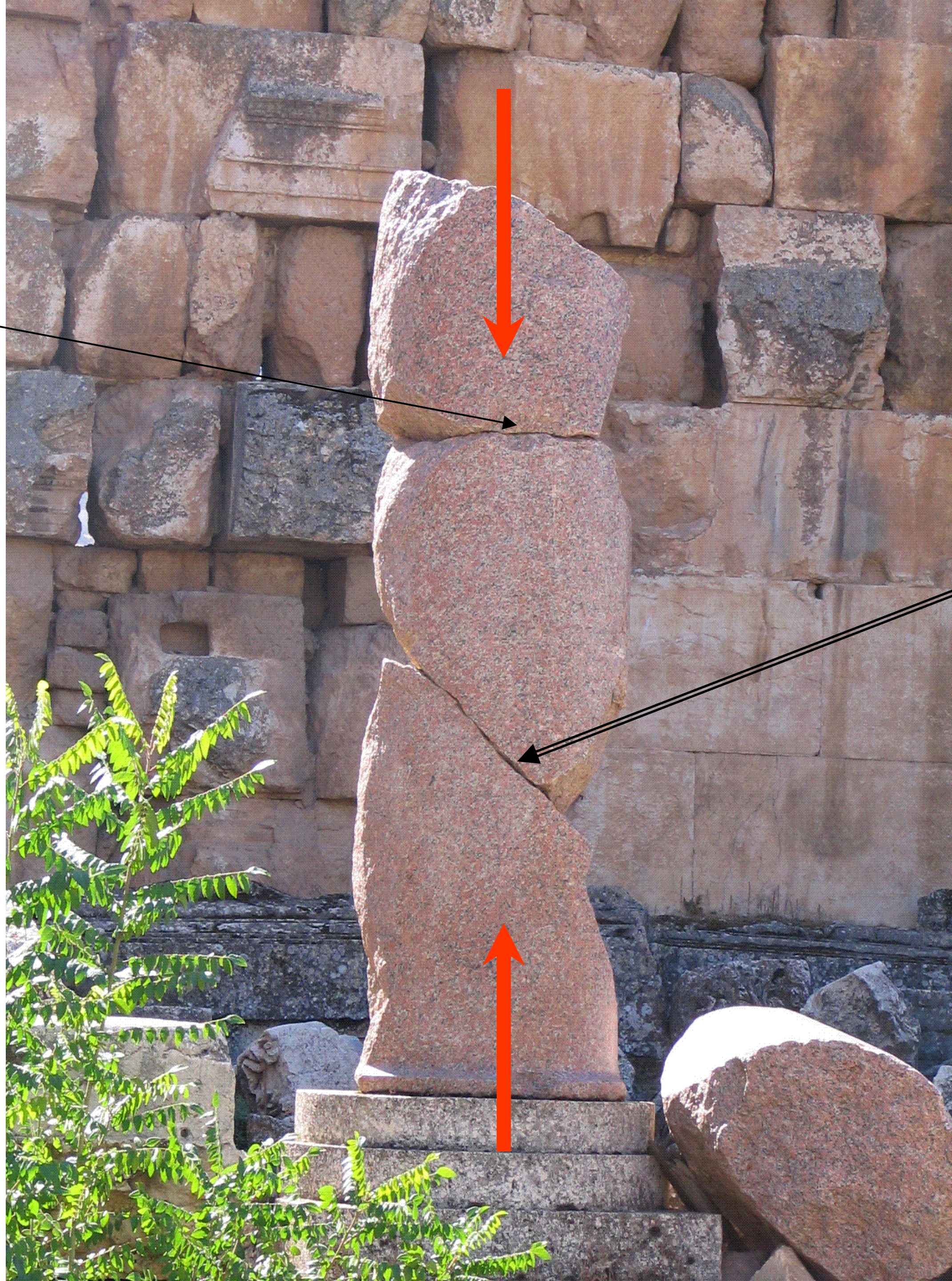


= hill of fragments (crumbs) as result of compression tests

t = tension
c = compression
R = strength, resistance
F = Fracture

Observed: ► **Each single Failure Mode is governed by one single strength, only !!**

just a joint

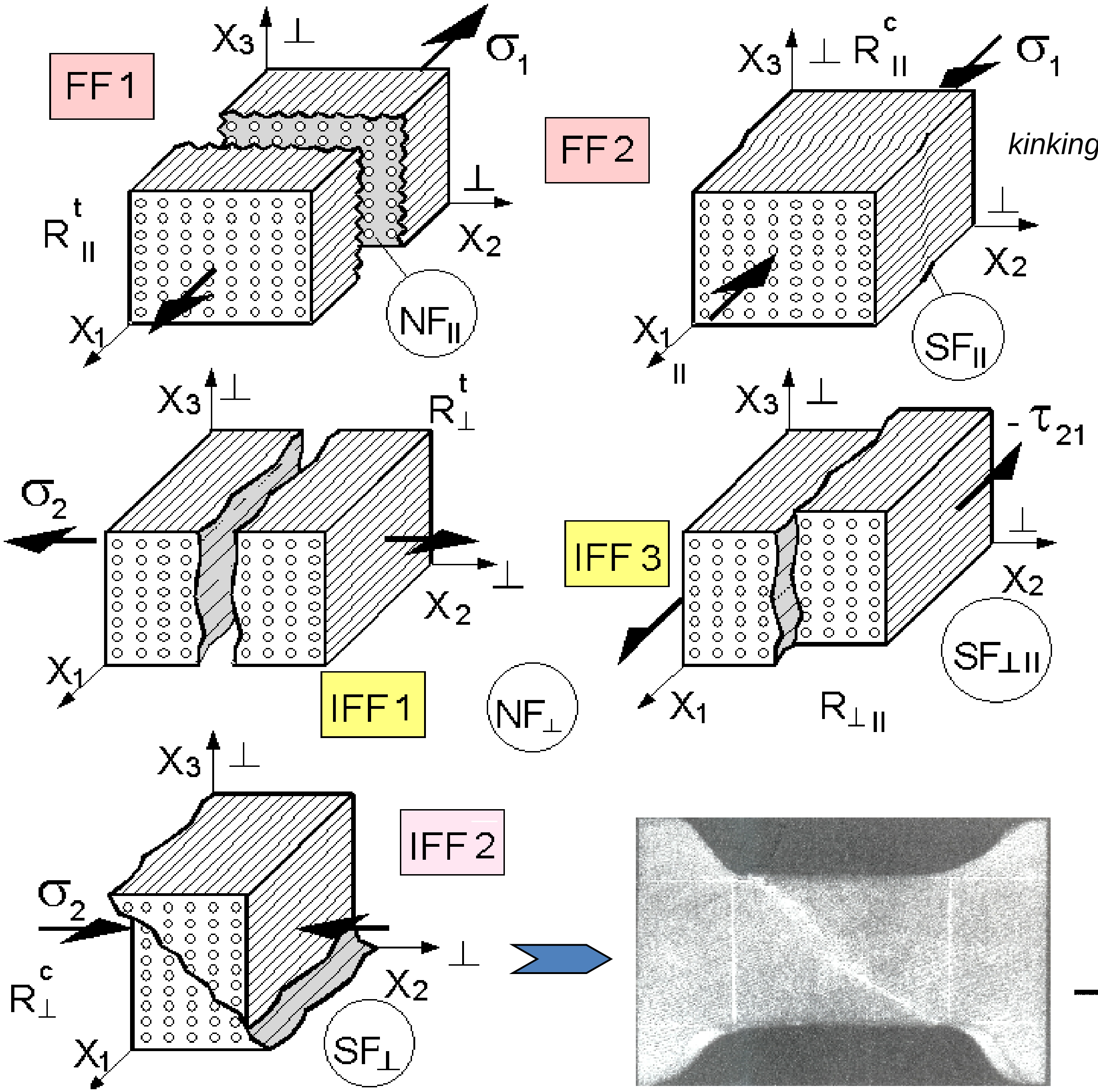


Example SF : R_m^c

Shear Fracture plane under compression

(Mohr-Coulomb, acting *at* a *rock material column, at Baalbek, Libanon)*

Test-observed Strength Failure Modes of Brittle behaving UD-Materials



wedge failure type

t = tension
c = compression

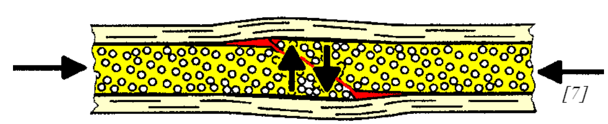
► 5 Fracture modes exist

= 2 FF (Fibre Failure)
+ 3 IFF (Inter Fibre Failure)

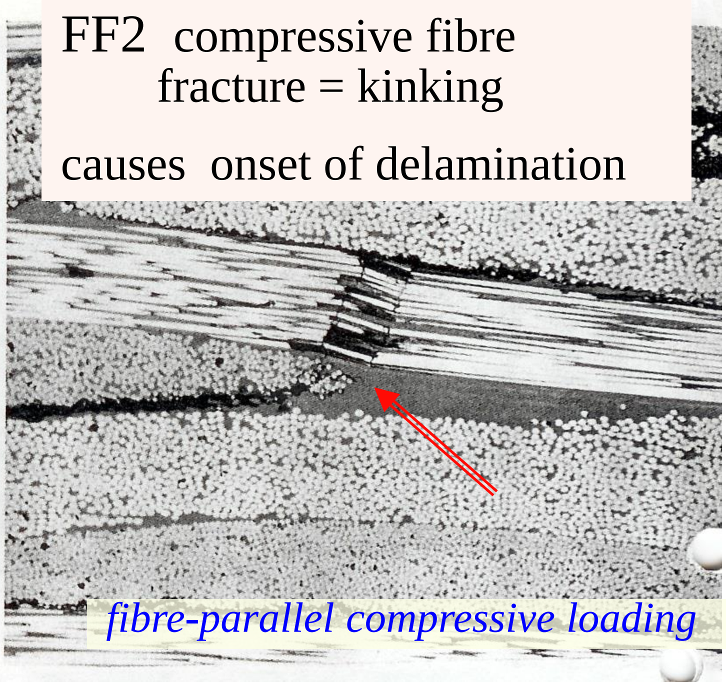
Fracture Types (macroscale-associated):

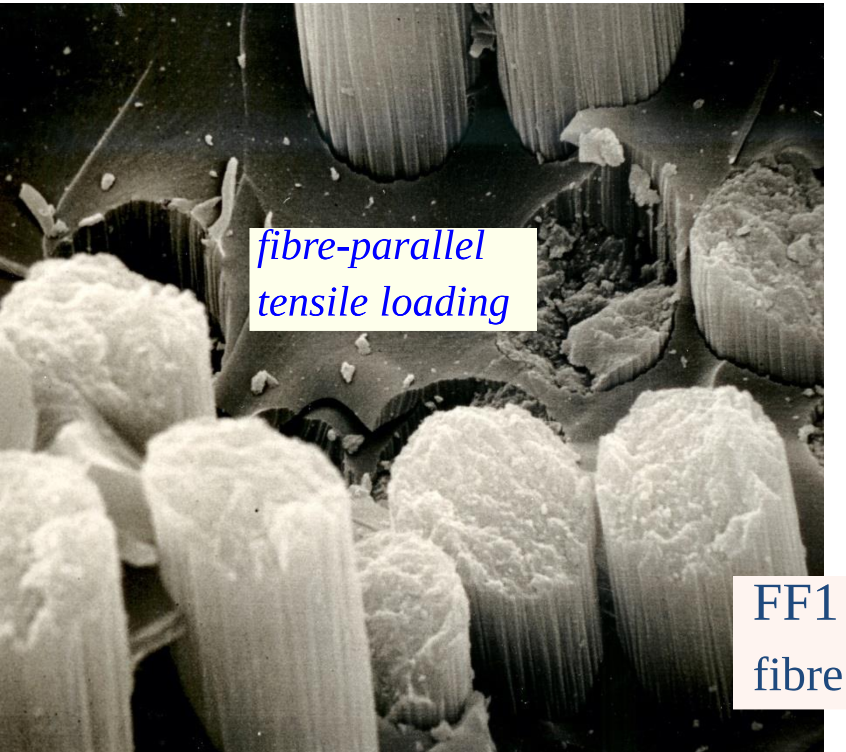
NF := Normal Fracture SF := Shear Fracture

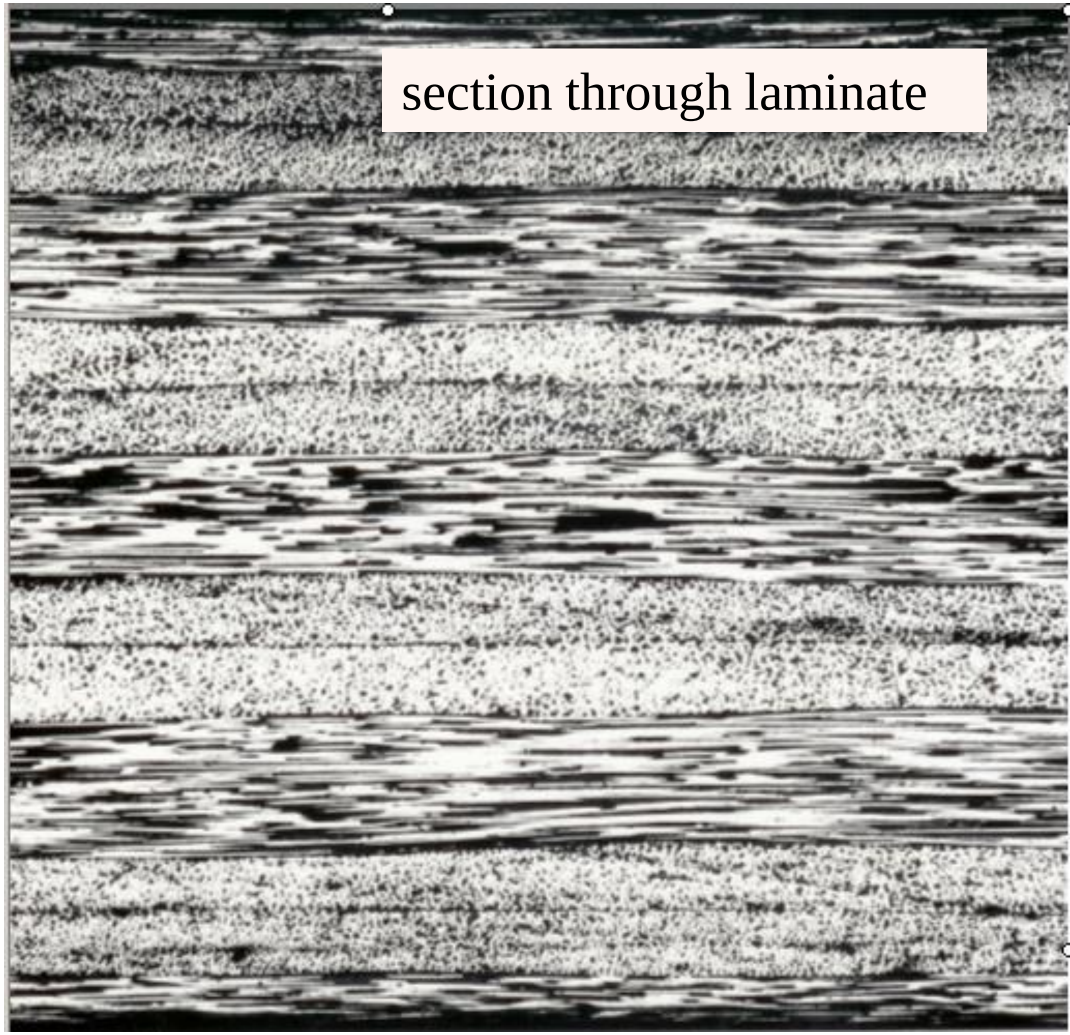
Friction occurs in IFF2 and IFF3 !



embedded UD lamina







Fractography pictures as proofs

Cuntzes 3D Modal Strength Failure Cond. (criteria) for Isotropic Foams

Approaches: $\frac{\sqrt{4J_2 - I_1^{\,2}/3} + I_1}{2 \cdot \bar{R}_t} = 1$ $\qquad$ $\frac{\sqrt{4J_2 - I_1^{\,2}/3} - I_1}{2 \cdot \bar{R}_c} = 1$

Considering bi-axial strength (failure mode occurs twice**):** **in Effs now**

$$Eff^{NF} = c_{NF} \cdot \frac{\sqrt{4J_2 - I_1^{\,2} \cdot (\Theta_{NF})/3} + I_1}{2 \cdot \bar{R}_t} = \sigma_{eq}^{NF} / \bar{R}_t \,, \qquad Eff^{CrF} = c_{CrF} \cdot \frac{\sqrt{4J_2 - I_1^{\,2} \cdot (\Theta_{CrF})/3} - I_1}{2 \cdot \bar{R}_c} = \sigma_{eq}^{CrF} / \bar{R}_c$$

The two-fold failure danger can be excellently modelled by using the often used invariant J3 in :

$$\Theta_{NF} = \sqrt[3]{1 + D_{NF} \cdot \sin(3\theta)} = \sqrt[3]{1 + D_{NF} \cdot 1.5 \cdot \sqrt{3} \cdot J_3 \cdot J_2^{-1.5}} \qquad \Theta_{CrF} = \sqrt[3]{1 + D_{CrF} \cdot \sin(3\theta)} = \sqrt[3]{1 + D_{CrF} \cdot 1.5 \cdot \sqrt{3} \cdot J_3 \cdot J_2^{-1.5}}$$

Mode interaction: $Eff^{NF} = [(Eff^{NF})^m + (Eff^{CrF})^m]^{m^{-1}}$

The failure surface is closed at both the ends: A simple cone serves as closing cap and bottom

$$\frac{I_1}{\sqrt{3} \cdot R_t} = s_{NF} \cdot \left(\frac{\sqrt{2J_2 \cdot \Theta_{NF}}}{R_t}\right) + \frac{\max I_1}{\sqrt{3} \cdot R_t}$$

Rt-normalized Lode-Coordinates

$$\frac{I_1}{\sqrt{3} \cdot R_t} = s_{CrF} \cdot \left(\frac{\sqrt{2J_2 \cdot \Theta_{CrF}}}{R_t}\right) + \frac{\min I_1}{\sqrt{3} \cdot R_t}$$

The slope parameters *s* are determined connecting the respective hydrostatic strength point with the associated point on the shear meridian, *maxI1* must be assessed whereas *minI1* could be measured.

Eff = material stressing effort = Werkstoff-Anstrengung *(must be < 1 = 100%)*

Cuntzes 3D Modal SFCs (criteria) for Transversely-Isotropic UD-materials

Invariants replaced by their stress formulations

strains from FEA [Cun04, Cun11]

FF1 $Eff^{\parallel\sigma} = \breve{\sigma}_1 / \bar{R}^t_{\parallel} = \sigma^{\parallel\sigma}_{eq} / \bar{R}^t_{\parallel}$, $\breve{\sigma}_1 \cong \varepsilon^t_1 \cdot E_{\parallel}$ *

FF2 $Eff^{\parallel\tau} = -\breve{\sigma}_1 / \bar{R}^c_{\parallel} = +\sigma^{\parallel\tau}_{eq} / \bar{R}^c_{\parallel}$, $\breve{\sigma}_1 \cong \varepsilon^c_1 \cdot E_{\parallel}$

2 filament modes

IFF1 $Eff^{\perp\sigma} = [(\sigma_2 + \sigma_3) + \sqrt{(\sigma_2 - \sigma_3)^2 + 4\tau_{23}^{\ 2}}\,] / 2\bar{R}^t_{\perp} = \sigma^{\perp\sigma}_{eq} / \bar{R}^t_{\perp}$

IFF2 $Eff^{\perp\tau} = [(\frac{\mu_{\perp\perp}}{1-\mu_{\perp\perp}}) \cdot (\sigma_2 + \sigma_3) + \frac{1}{1-\mu_{\perp\perp}} \sqrt{(\sigma_2 - \sigma_3)^2 + 4\tau_{23}^{\ 2}}\,] / \bar{R}^c_{\perp} = +\sigma^{\perp\tau}_{eq} / \bar{R}^c_{\perp}$

IFF3 $Eff^{\perp\parallel} = \{[\mu_{\perp\parallel} \cdot I_{23-5} + (\sqrt{\mu_{\perp\parallel}^{\ 2} \cdot I_{23-5}^{\ 2} + 4 \cdot \bar{R}_{\perp\parallel}^{\ 2} \cdot (\tau_{31}^2 + \tau_{21}^2)^2}\,]/(2 \cdot \bar{R}_{\perp\parallel}^{\ 3})\}^{0.5} = \sigma^{\perp\parallel}_{eq} / \bar{R}_{\perp\parallel}$

3 matrix modes

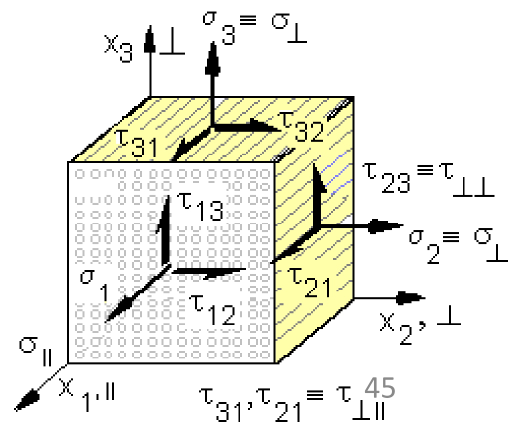
with $I_{23-5} = 2\sigma_2 \cdot \tau_{21}^2 + 2\sigma_3 \cdot \tau_{31}^2 + 4\tau_{23}\tau_{31}\tau_{21}$

Modes-Interaction :

$$Eff^{m} = (Eff^{\parallel\tau})^m + (Eff^{\parallel\sigma})^m + (Eff^{\perp\sigma})^m + (Eff^{\perp\tau})^m + (Eff^{\perp\parallel})^m = 1$$

with mode-interaction exponent $2.5 < m < 3$ from mapping tests data

Typical friction value data range: $0.05 < \mu_{\perp\parallel} < 0.3, \quad 0.05 < \mu_{\perp\perp} < 0.2$



Poisson effect * : bi-axial compression strains the filament without any σ_1

t:= tensile, c: = compression, || : = parallel to fibre, ⊥ := transversal to fibre

Interaction of Single Strength Failure Modes in the modal FMC

Interaction of adjacent Failure Modes by a *series failure system* model

= 'Accumulation' of interacting *failure danger portions* Eff^{mode}

$$Eff^{*} = \sqrt[m]{(Eff^{\text{mode 1}})^{m} + (Eff^{\text{mode 2}})^{m} + \ldots}$$ $= 1 = 100\%$ *, if failure*

with mode-interaction exponent *2.5 < m < 3 from mapping experience*

as modal **material stressing effort * (in German Werkstoffanstrengung)**

and

$$Eff^{\text{mode}} = \sigma_{eq}^{\text{mode}} / \overline{R}^{\text{mode}}$$

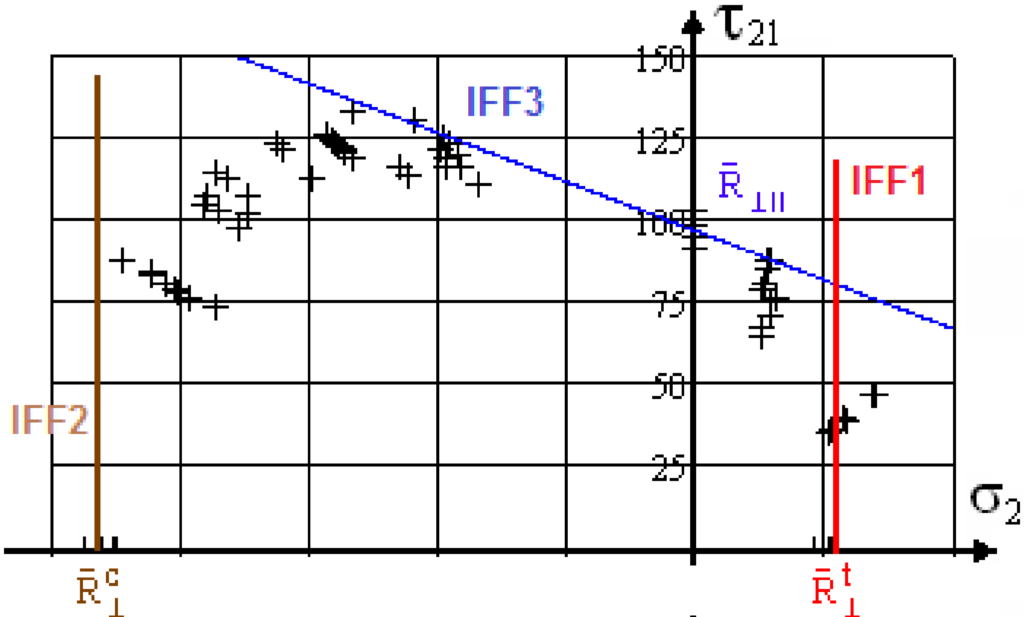
equivalent mode stress

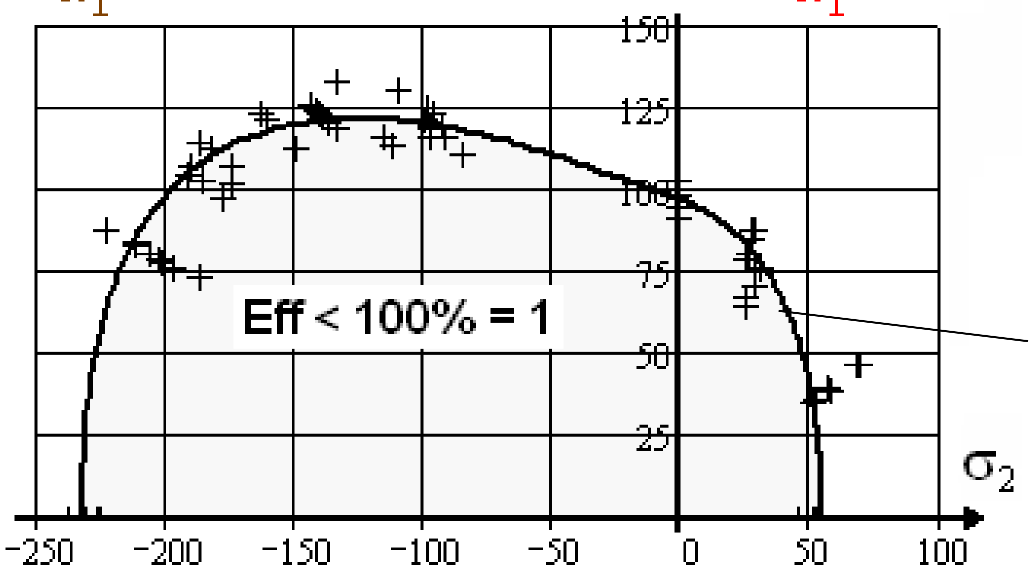
mode associated average strength

example

*** artificial technical term** created together with QinetiQ in the World-Wide-Failure-Exercise

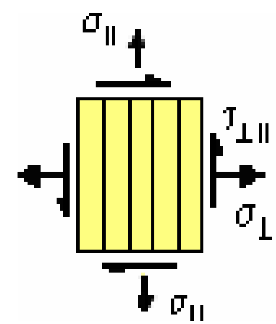
2D-Demonstration: Interaction of UD Failure Modes for $\tau_{21}(\sigma_2)$, $\breve{\sigma}_1 = 0$





Mapping of course of IFF test data in a pure mode domain by the associated *Mode Failure Condition.*

3 IFF pure modes = straight *lines !.*



IFF 1 : $\frac{\sigma_2}{\bar{R}_\perp^t} = 1$

IFF 2 : $\frac{-\sigma_2}{\bar{R}_\perp^c} = 1$

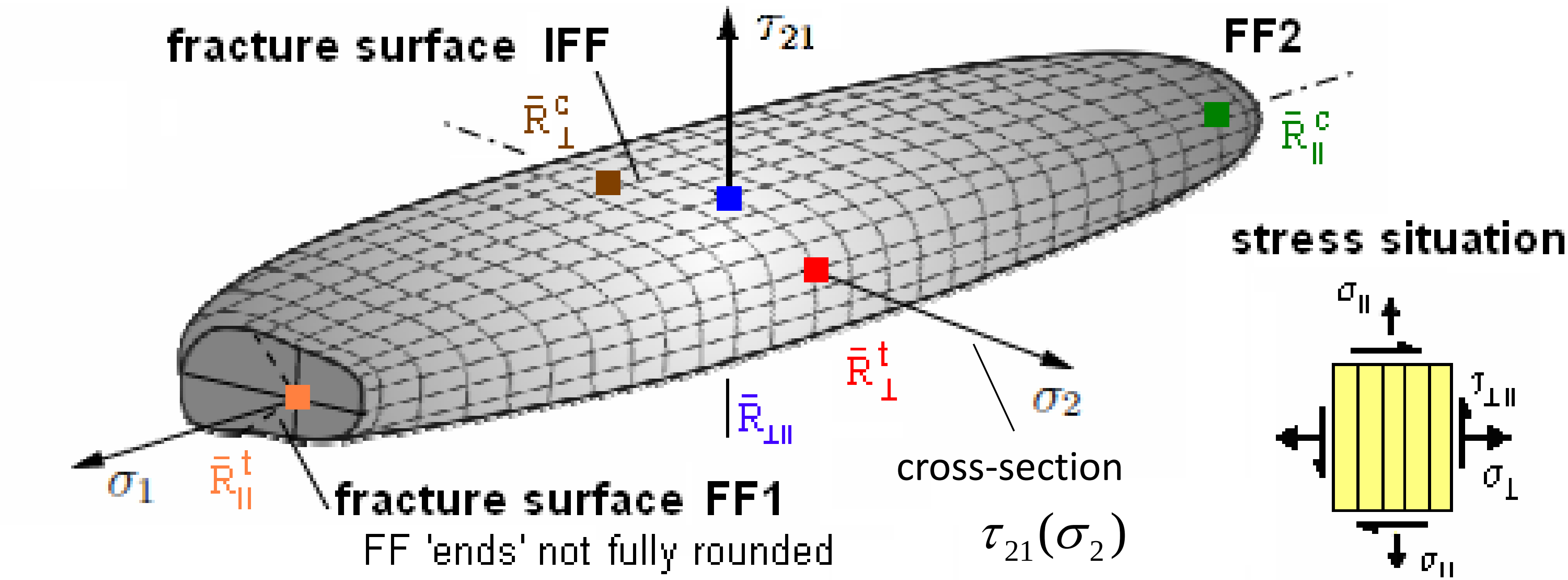
IFF 3 *(2D-simplified)* : $\frac{|\tau_{21}|}{\bar{R}_{\perp\parallel} - \mu_{\perp\parallel} \cdot \sigma_2} = 1$

Mapping of course of test data by
Interaction Model

$$(Eff^{\perp\sigma})^m + (Eff^{\perp\tau})^m + (Eff^{\perp\parallel})^m = 1$$

$$m = 2.5, \quad \mu_{\perp\parallel} = 0.3$$

Visualization of 2D-UD-SFCs as Fracture Failure Surface (Body)



$$\{\sigma\} = (\sigma_1, \sigma_2, 0, 0, 0, \ \tau_{21})^T$$

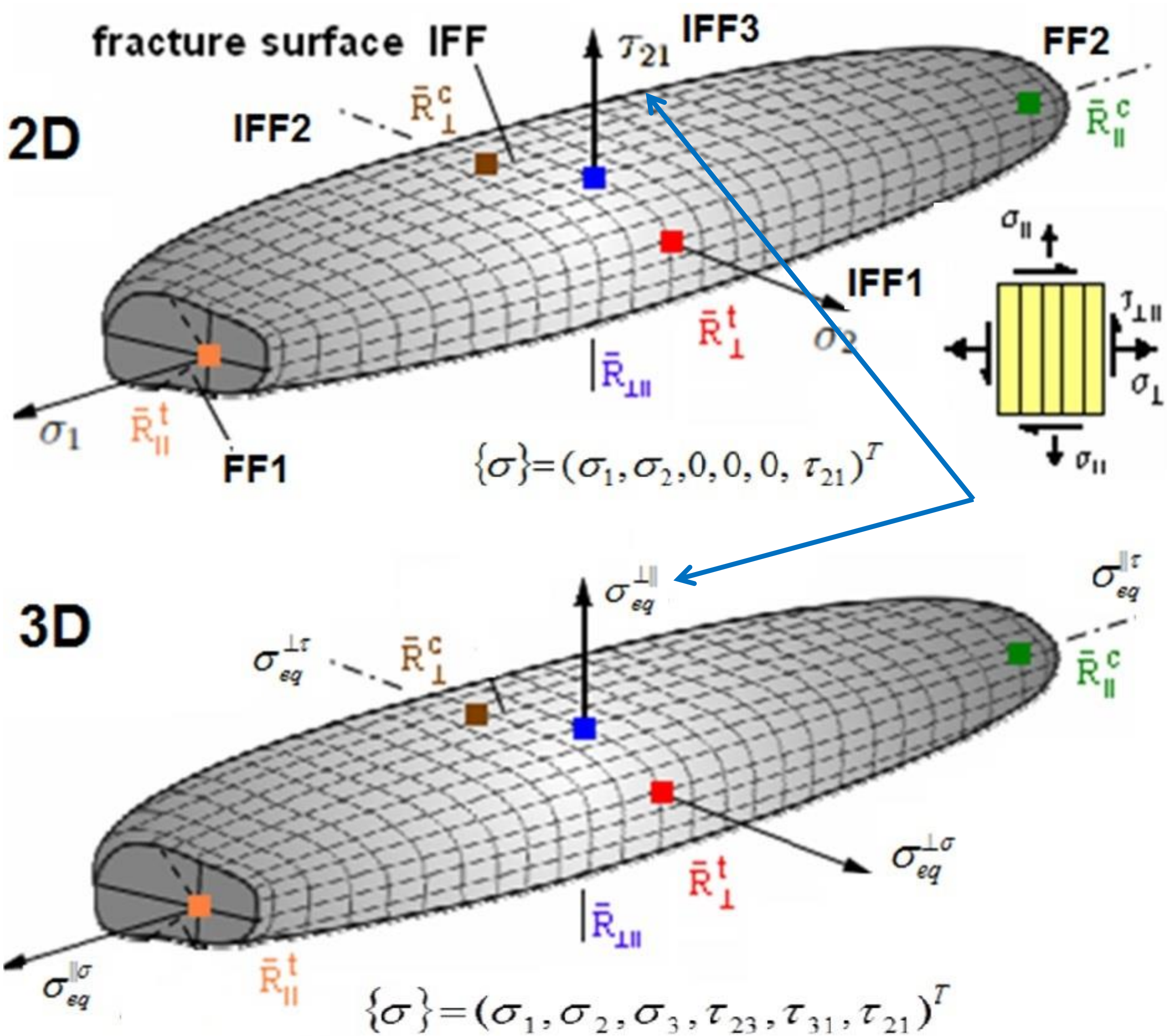
Mode interaction fracture failure surface *of FRP UD lamina*

$$Eff^{\,m} = \ (Eff^{\,\parallel\tau})^m + (Eff^{\,\parallel\sigma})^m + \ (Eff^{\,\perp\sigma})^m + \ (Eff^{\,\perp\tau})^m + \ (Eff^{\,\perp\parallel})^m = \ 1$$

(courtesy W. Becker) .

Mapping: Average strengths indicated

2D = 3D Fracture surface if replacing *stresses* by *equivalent stresses*



Short Presentation of CCeV + personal activities

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Specific Pre-requisites for the establishment of 3D-UD-SFCs:

- simply formulated from engineering point of view, numerically robust,
- physically-based, and therefore need only few information for pre-dimensioning
- shall allow for a simple determination of the design driving reserve factor
- shall capture failure of the constituents matrix (cohesive), interphase (adhesive), filament
- consider residual stresses

Compliant with John Hart-Smith

- consider micro-mechanical stress concentration of the matrix around the filaments under transversal stress (a means: using matrices showing > 6% fracture strain which heps to capture a stress concentration factor of about 6 up to 1% applied transversal strain
- consider FF, if taking place under bi-axial compression with no external axial stress

$$\{\sigma\} = (\sigma_1 = 0,\ \sigma_2,\ \sigma_3, 0, 0, 0)^T$$

Example: Assumptions for UD Modelling and Mapping

- The UD-lamina is macroscopically homogeneous. It can be treated as a homogenized ('smeared') material *Homogenisation of a solid to a material brings benefits*.

Then Knowledge of Material Symmetry applicable : number of required material properties are minimal, test-costs too

1 Lamina (ply) = Layer of a Laminate, e.g. UD-laminas = "Bricks"

- The UD-lamina is transversely-isotropic: On planes, parallel to the fiber direction it behaves orthotropic and on planes transverse to fiber direction isotropic (quasi-isotropic plane)

- Mapping creates fidelity, only, if: uniform stress states are about the critical stress location in the material ! Is very seldom the case.

Motivation for my non-funded Investigations

Existing Links in the Mechanical Behaviour show up: *Different structural materials*

- *can possess similar material behaviour or*
- *can belong to the same class of material symmetry*

〉 similarity aspect

Welcomed Consequence:

- The same strength failure function F can be used for different materials
- More information is available for pre-dimensioning + modelling from experimental results of a similarly behaving material.

Background: *Author's experience with structural material applications, range 4 K - 2000 K*

Basic Features of the author‘s Failure-Mode-Concept (FMC)

- **Each failure mode represents 1 independent failure mechanism and thereby 1 piece of the complete *failure surface***
- **Each failure mechanism is governed by 1 basic strength** (is observed !)
- **Each failure *mode* can be represented by 1 failure *condition.*** *Therefore, equivalent stresses can be computed for each mode !*

- **In consequence, this separation requires :**

  An interaction of the Modal Failure Modes !

Failure-Mode-Concept (FMC) Postulate (*example*: UD material)

Remember:

- Each single observed fracture failure modes is linked to one strength
- Symmetry of a material showed : *Number of strengths =* $R_{||}^{t}, R_{||}^{c}, R_{\perp||}, R_{\perp}^{t}, R_{\perp}^{c}$

number of elasticity properties ! $E_{\parallel}, E_{\perp}, G_{\parallel\perp}, \nu_{\perp\parallel}, \nu_{\perp\perp}$

Due to the facts above Cuntze postulates in his FMC

▶ Number of failure modes = number of strengths, too !

e.g.: isotropic = 2 or above transversely-isotropic (UD) = 5

t:= tensile, c: = compression, || : = parallel to fibre, := transversal to fibre

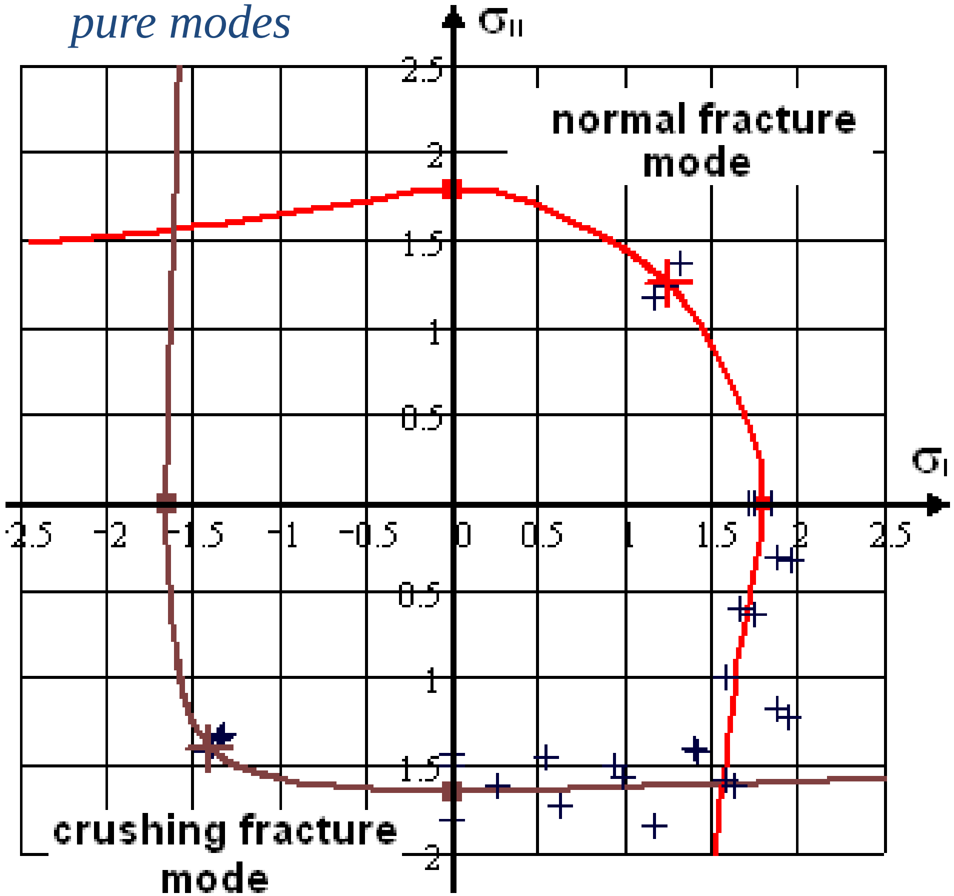
1 Introduction to Strength Failure Conditions (SFCs)
2 Fundamentals when generating SFCs (criteria)
3 Global SFCs versus Modal SFCs
4 Requirements
5 Short Derivation of the Failure-Mode-Concept (FMC)
6 FMC-model applied to an Isotropic Foam (Rohacell 71 G)
7 FMC-model applied to a transversely-isotropic UD-CFRP
Conclusions

2D - Test Data Set and Mapping in the Principal Stress Plane

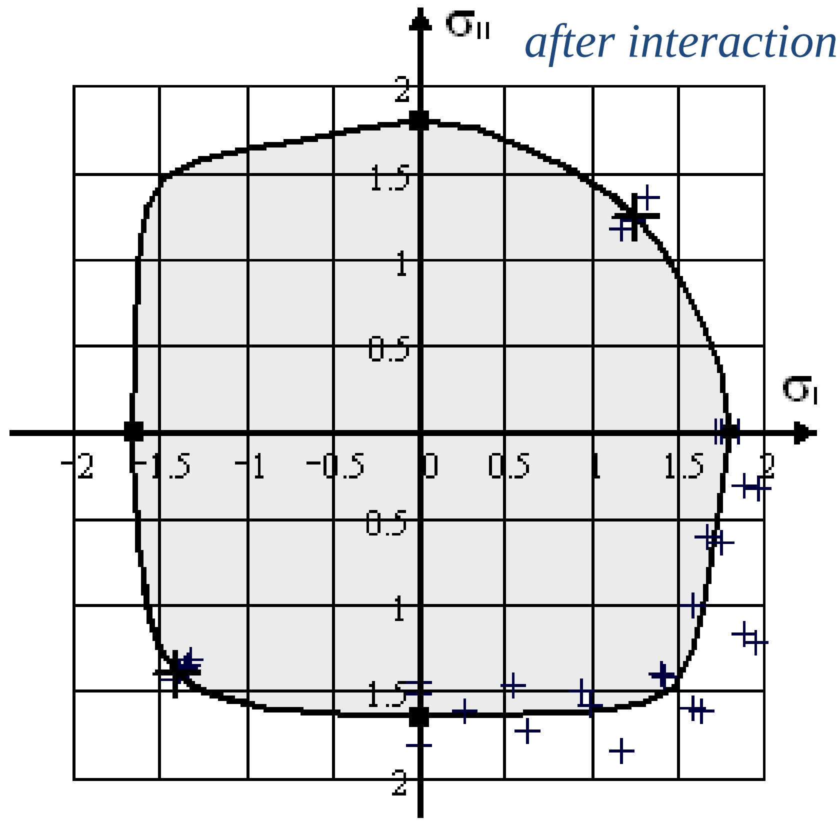
Rohacell 71 IG

Principal Stress Plane Cross-section of the Fracture Body (oblique cut) as similarly behaving material

pure modes



after interaction

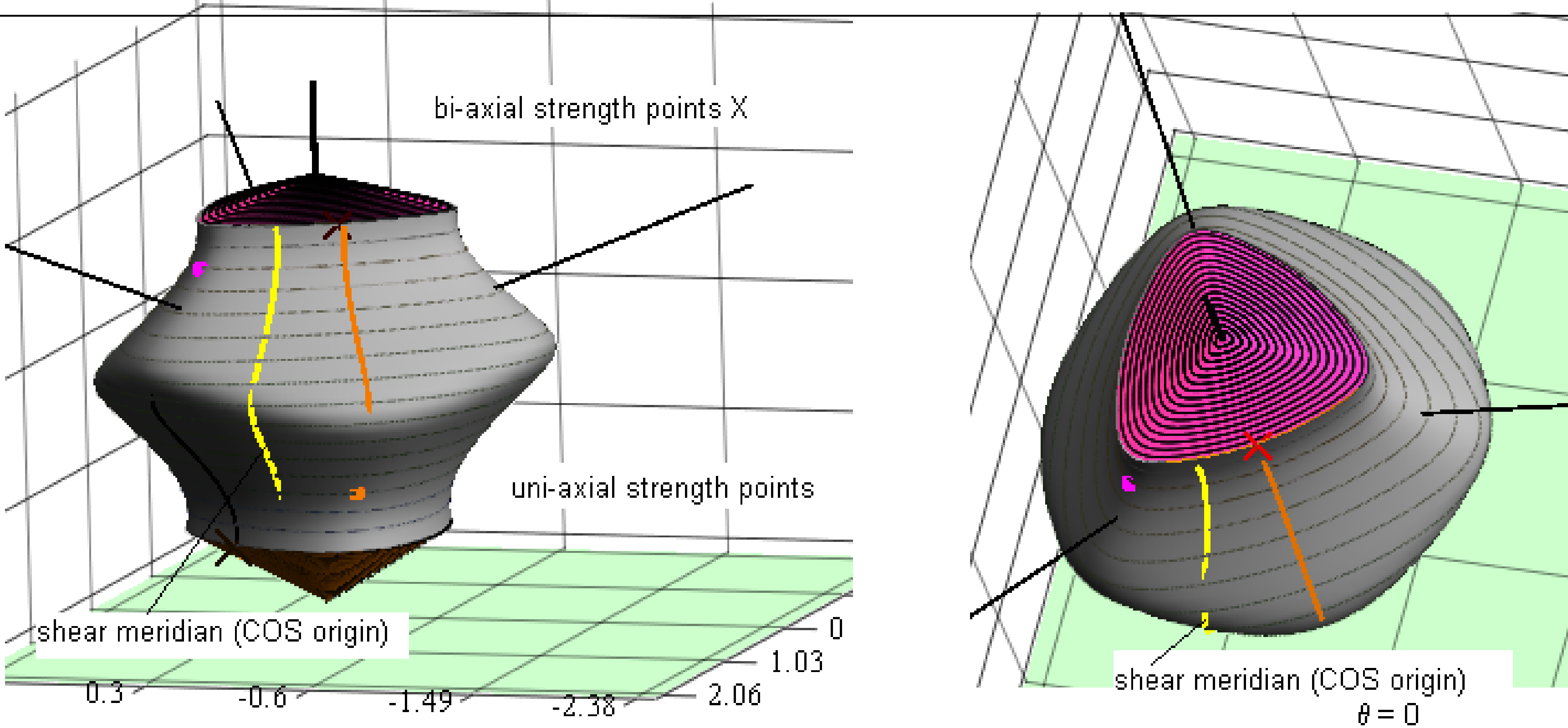


- **Mapping <u>must</u> be performed in the 2D-plane because fracture data set is given there**
- **The 2D-mapping uses the 2D-subsolution of the 3D-strength failure conditions**
- **The 3D-fracture failure surface (body) is based on the 2D-derived model parameters.**

Courtesy: LBF-Darmstadt, Dr. Kolupaev

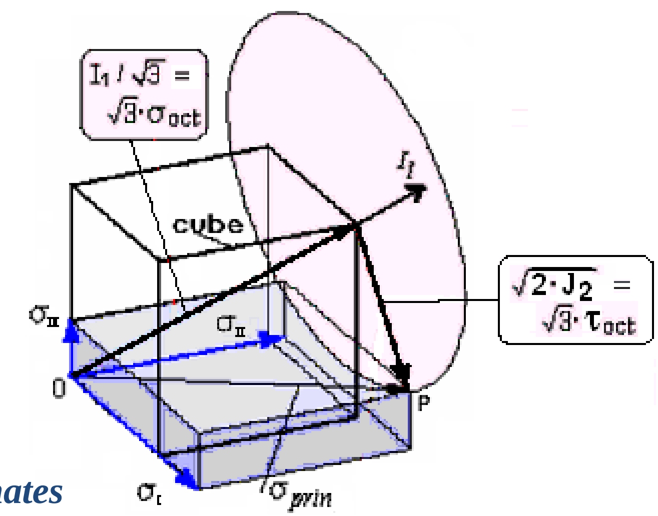
Fracture Failure Surface of *Rohacell 71 IG*

The dent turns !



compressive meridian with tensile meridian form one cross-section shape

The 3D-strength failure condition enables to predict the 120°-symmetric failure body and to judge a 3D- stress state



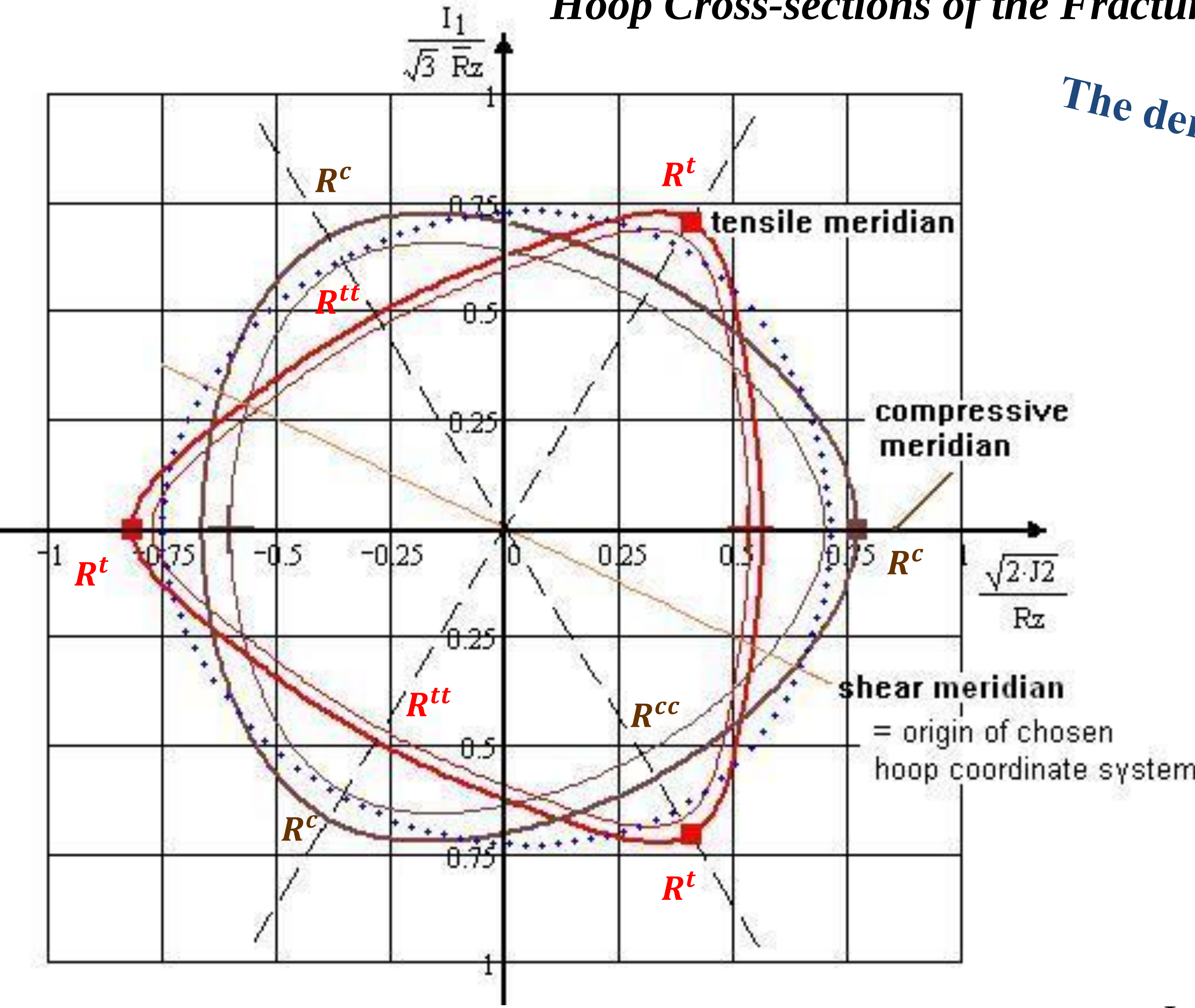
visualization of the Lode-Haigh-Westergaard coordinates

2D Test Data and Mapping in the Octahedral Stress Plane

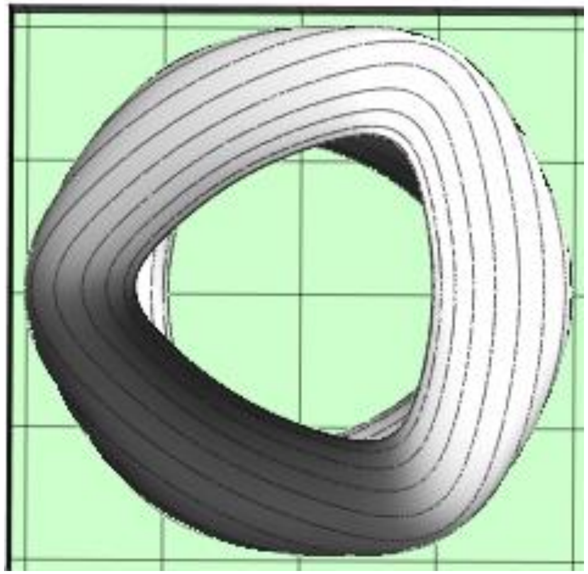
Rohacell 71 IG

as similarly behaving material

Hoop Cross-sections of the Fracture Body



The dent turns !



Caps: No test data, cone was chosen.

Lode-angle, here set as $\sin(3\,\theta)$:

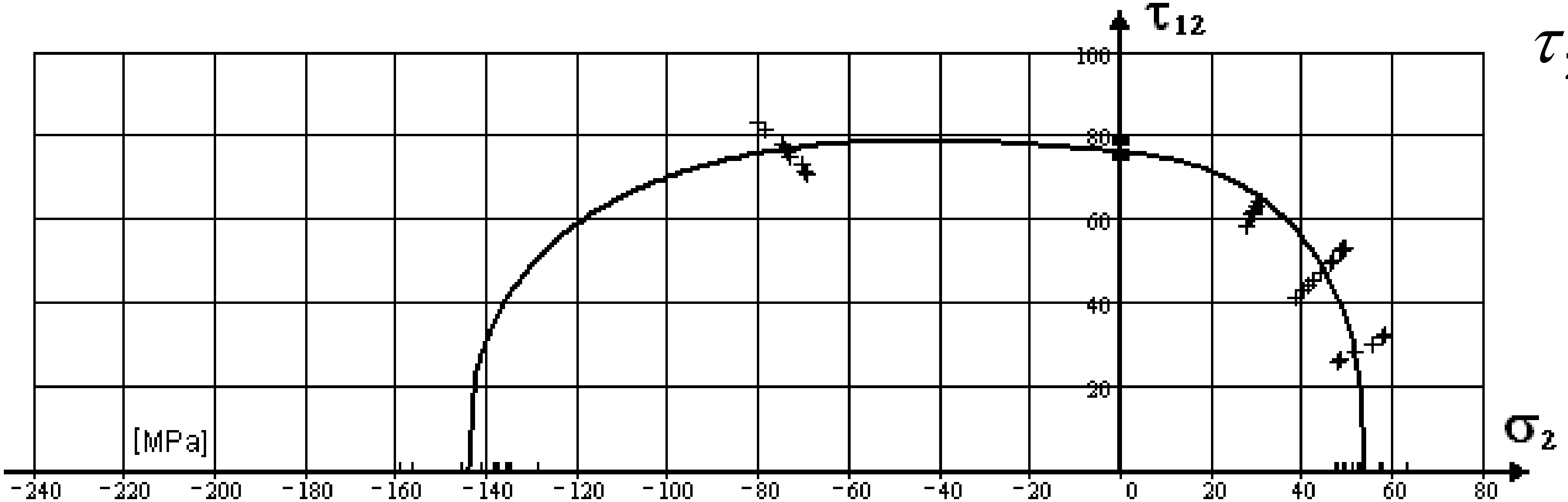
shear meridian angle = 0°

tensile meridian +30° +

compressive meridian -30° +

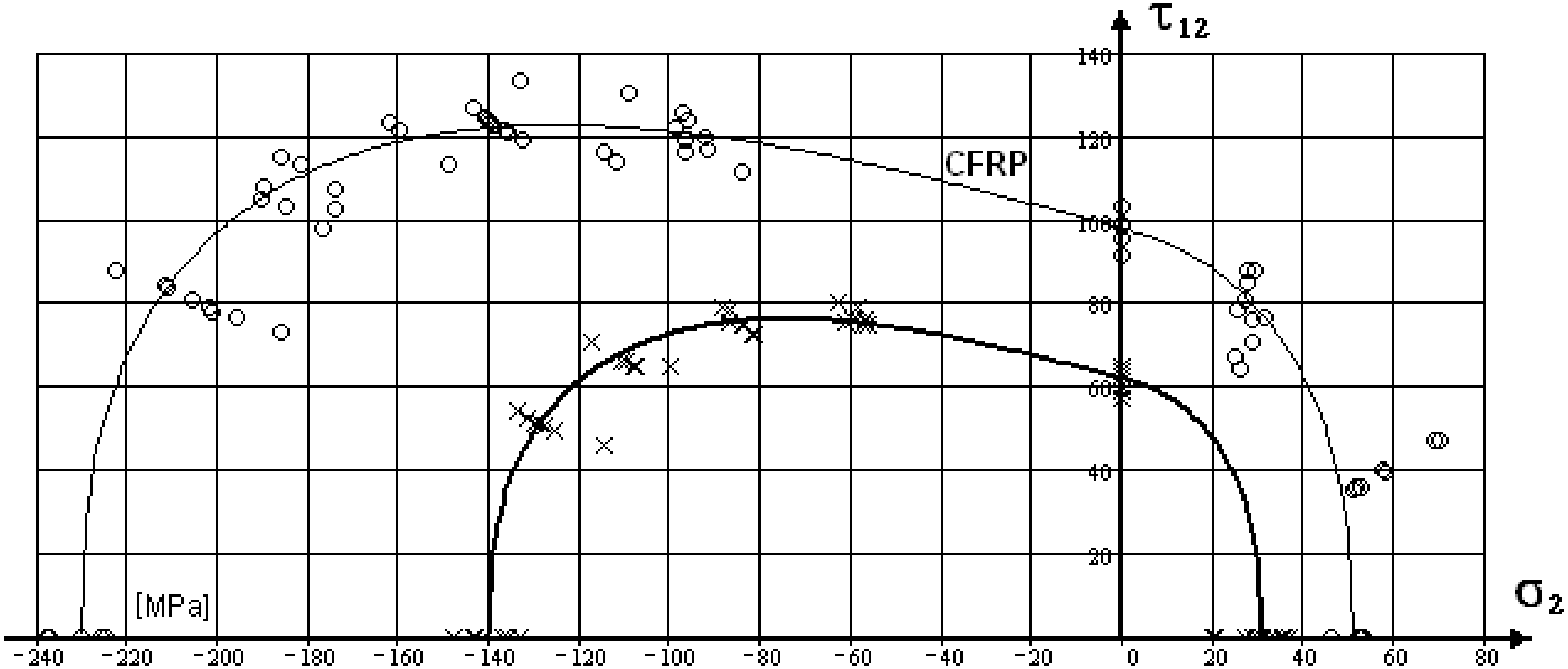
I1 = 0, is interaction domain: Is about a circle.

GFRP, CFRP examples, mapped by FMC–based UD SCF, 2D stress state



$\tau_{21}(\sigma_2)$

IFF



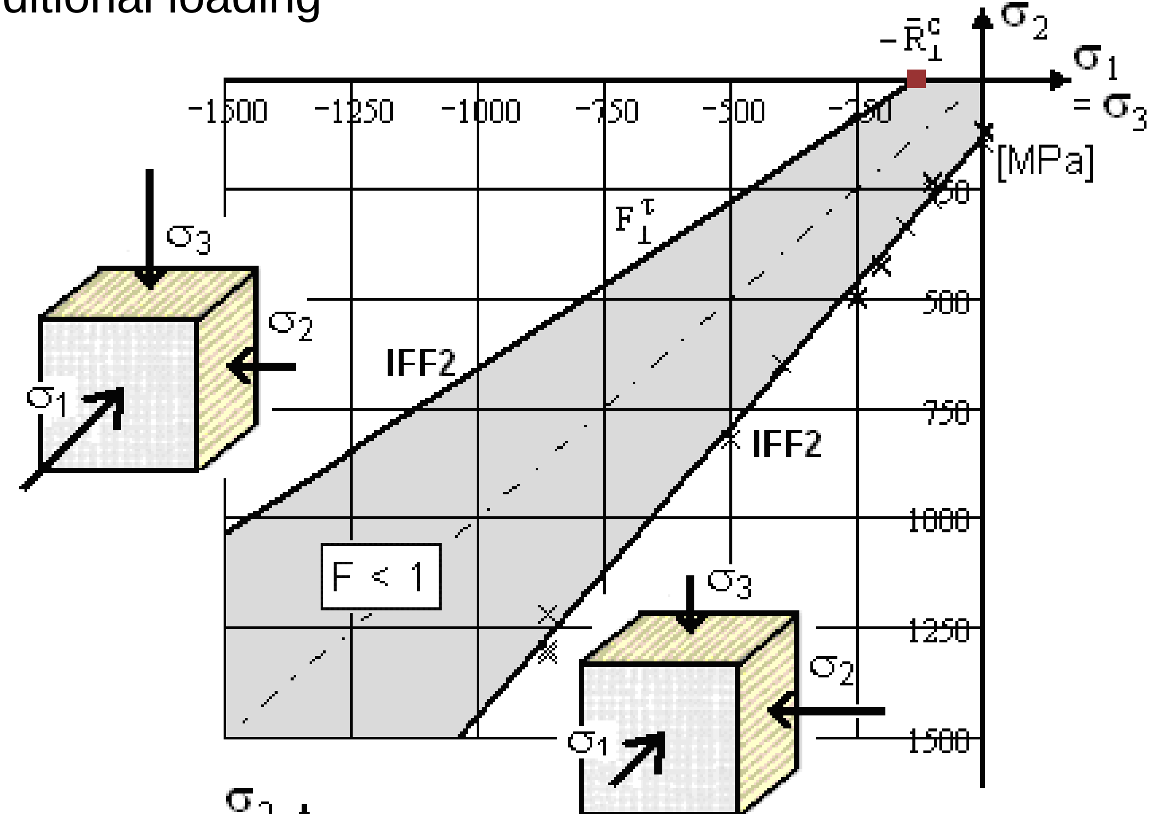
Test Case 5, WWFE-II, UD test specimen, 3D stress state $\sigma_2(\sigma_1 = \sigma_3)$

= hydrostatic pressure with additional loading

UD E-glass/MY750epoxy.

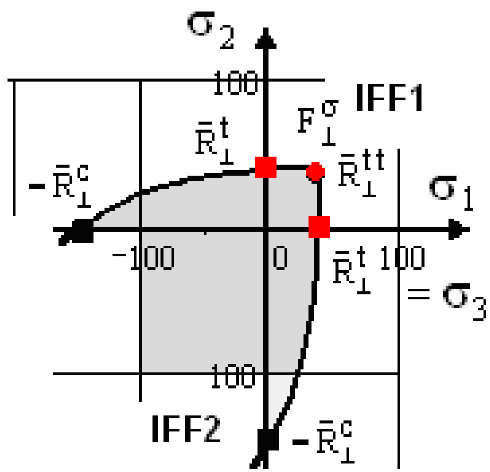
$\nu_{\perp\parallel} = 0.28, \quad \mu_{\perp\perp} = 0.14, \quad m = 2.8$,

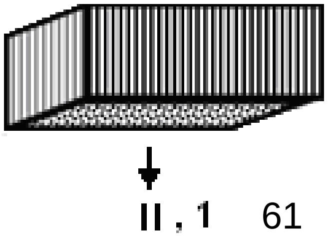
$\{\bar{R}\} = (1280,\ 800,\ 40,\ 132,\ 73)^T\ MPa$



Good Mapping, <u>after</u> QinetiQ re-evaluation of the lower branch test data Then, the upper branch was fitting other test data, too !

Result: *Both branches were then reliable and could be used for model validation*





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9. **Standardized Material Test Methods** **Kollege**
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What is Fatigue ? = process, that degrades material properties

What is Damaging? not damage, as used in English literature

Process wherein the results, the damaging portions, finally accumulate to a damage size such as a macro-scopic delamination.

The means is usually *Miner's Damaging Accumulation* model

What is Damage?

If above damage size is judged to be critical, then Damage Tolerance Analysis is used to predict its growth under further cyclic loading.

State-of-the-Art in Cyclic Strength Analysis of UD Laminas (plies), Laminates

• Procedures base on specific laminates and therefore cannot be generally applied.
Hence, no generally applicable Lifetime Prediction Method is available !

• Procedures base – as with metals – on stress amplitudes and mean stress correction. *Is this correct? Can one neglect that the damaging portions are linked to the various fracture failure modes in the case of brittle behaving materials?*

• Present: Engineering Approach: *Static Design Limit Strain* of < 0.3% , negligible matrix-microcracking.
Design experience proved: No fatigue danger is given for multi-angle laminates

• Future : *Design Limit Strain* shall be increased for better material exploitation
(EU-project: MAAXIMUS)
Above $\varepsilon = 0.5\%$ level: *first filament breaks , diffuse matrix-microcracking* occurs in usually *fiber-dominated laminates*, used in high-stress applications.

To tackle this, much effort must be put on this in future !

Was sind die benötigten zyklischen Eigenschaften?

- Wöhlerkurven $R = const = \sigma_{unter} / \sigma_{ober}$
- Schädigungsakkumulationshypothese
- Quantifizierte Schädigungs‘portionen‘ (-inkremente)

Dazu Anwendbarkeit der statischen Festigkeitshypothesen, wenn die

Statischen Festigkeitswerte durch

Restfestigkeitswerte für eine bestimmte Lebensdauer

ersetzt werden.

Statische Anstrengungssumme *Eff* (material stressing effort)

wird durch

Zyklische Schädigungssumme ***D***

ersetzt !

State of the Art in Cyclic Strength Analysis of UD Laminas (plies)

- **No Lifetime Prediction Method available, applicable to any Laminate**
- **Procedures base – as with metals – on stress amplitudes and mean stress correction**
- **Procedures base on specific laminates and therefore cannot be generally applied**
- **Present: Engineering Approach:**

  ***Static Design Limit Strain* of < 0.3% ,** negligible matrix-microcracking.

  Design experience proved: No fatigue danger given

- **Future : *Design Limit Strain* shall be increased** (EU-project: MAAXIMUS)

  We must react!

  Above ε= 0.5% *first filament breaks* , *diffuse matrix-microcracking* occurs

  in usually *fiber-dominated laminates* used in high-stress applications .

⇨

Questions an engineer poses in the case of cyclic design

1. When does damaging start?
2. How can one consider the single (micro-)damaging portion?
3. How are the single damaging portions accumulated?
4. When do the accumulated damageing portions form a damage?
5. When becomes such a damage (delamination, impact) critical?
6. How is the damage growth in the 3rd or final phase of fatigue life (fixation of part replacement time, inspection intervals)?

1 Foundation of the German Academic Research Group (BeNa)
“*Betriebsfestigkeits-Nachweis*“
for High-Performance Structures (2010)

* *physically-based (on failure modes),*
* *ply-oriented in order to obtain a generalisation for any UD lamina-composed laminate*

Objective:
Release of a VDI-Guideline

2 Foundation of sub-group of my CCeV-working group ‘Engineering‘
“*Composite Fatigue*“
together with the CCeV member company CADCON (2012).

FMC-based UD Strength Failure Conditions

Damaging drivers

- **Ductile material behaviour (e.g. many metals):**

**** Slip band shear yielding - as damaging driver - occurs under cyclic tensile stress, compressive stress, and under shear stress !***

**** Therefore, this single mechanism***

shear stress–caused yielding can be principally described by

<u>one</u> yield failure condition to determine the needed damaging portions !

(Formulation is in normal stresses, but the shear stress is the damaging driver).

**** Increasing with brittleness, lifetime estimation is corrected by accounting for the 'Mean stress effect' σ_{mean}***

(considers by Goodman Diagram that more mechanisms really act).

fatigue

topics

Brittle material behaviour :

**** Many mechanisms, causing damaging, must be considered***

Question is whether a correction by the 'Mean stress effect' makes sense.

Applicability of Static Strength Failure Conditions?

Proven Assumption:

If the damaging mechanisms (failure modes) are equal, then

- failure parameters that drive cyclic damaging are equal, too, and
- transferability from static failure to cyclic failure is permitted

However, static strength must be replaced by the fatigue strength = residual strength of the shrinking failure body.

Therefore,

as necessary static tool, my

FMC-based Static Failure Conditions (criteria) shall be briefly derived which

were very successful in the World-Wide-Failure-Exercise (WWFE 1992-2014).

From all the contributors, my *non-funded* Failure Conditions well mapped the largest number of test data courses in WWFE-I and WWFE–II !

Schritte bei der Lebensdauerabschätzung

1 Input

Betriebsbelastungen: Last-Zeit-Kurven (Modellierung mit rain flow, ..)

Sicherheitskonzept: Design to Life **j_{Life} = 3 – 4**

2 Übertragung der Betriebsbelastungen in Beanspruchungen (Spannungen) mittels Struktura**nalyse)

3 Bereiche der Ermüdungsanalyse

LCF: high stressing,

HCF: intermediate stressing

VHCF: low stressing and strains (SPP1466)

4 Erfassung der Betriebsbelastung

Zeitbereich: Zyklus-für-Zyklus oder Kollektiv-für-Kollektiv (weniger Rechenaufwand)

Frequenzbereich: Lastspektren (Verlust der Last-Reihenfolge) oder Blockbelastungen, etc.

Because *semi-brittle, brittle* behaving materials experience several failure modes or mechanisms.

Consequence:

More than one strength failure condition (criterion) must be employed

… and for the UD-composed brittle behaving laminates
with 5 failure modes
5 FMC strength failure conditions are considered !

Stress (not strain) criteria are applied to determine the subsequent damaging portions:

- capture the combined effect of lamina stresses and
- consider residual stresses from manufacturing cooling down (essential for HCF)

- ***Determination of damaging portions*** *(from diffuse and later discrete damaging)*
- ***Accumulation of damaging portions*** *(cycle-wise, block-wise, or otherwise ?)*

Experience with to-date Composites from fiber-reinforced plastics

- *behave brittle*
- *experience early fatigue damage*
- *show benign fatigue failure behaviour in case of 'well-designed', fiber-dominated laminates until final 'Sudden Death'.*

(fiber-dominated:= 0° plies in all significant loading directions, > 3 angles)

Schädigungstreiber bei spröden zyklisch beanspruchten Composites)

Annahmen: Falls Versagensmechanismen(-modi) gleich?

- Dann auch die schädigungstreibenden Versagensparameter gleich.
- Übertragbarkeit statisches Versagen auf Ermüdung möglich,

Dabei schädigen ebene (2D) und räumliche (3D) Spannungszustände

Meßbare Schädigungsgrößen:

Mikrorißdichte, Restfestigkeit, Reststeifigkeit

- **Duktiles Werkstoffverhalten** (Beispiel: isotrope Metalle)

  1 Mechanismus = "Schubspannungsgleiten"

  passiert unter allen zyklischen Beanspruchungen:

  Zugspannungen, Druckspannungen, Schub- und Torsionsspannungen !

  Deswegen kann dieser einzige Mechanismus 'Schubspannungsbasiertes Gleiten' mit einer einzigen Fließbedingung beschrieben werden!

- **Sprödes Werkstoffverhalten bei isotropen Werkstoffen**

  2 *Schädigung erzeugende* ***Mechanismen*** *wirken*

  (ingenieurmäßige Berücksichtigung durch sog. Mittelspannungskorrektur)

- **Sprödes Werkstoffverhalten bei UD- Werkstoffen**

  5 *Schädigung erzeugende* ***Mechanismen*** *wirken*

  (Ansätze mit und ohne Mittelspannungskorrektur)

Example: Fatigue of endless fiber-reinforced UD Laminates
Damaging drivers

- **Ductile material behaviour (e.g. many metals):**

**** Slip band shear yielding - as damaging driver - occurs under cyclic tensile stress, compressive stress, and under shear stress !***

**** Therefore, this single mechanism***

shear stress–caused yielding can be principally described by

<u>one</u> yield failure condition to determine the needed damaging portions !

(Formulation is in normal stresses, but the shear stress is the damaging driver).

**** Increasing with brittleness, lifetime estimation is corrected by accounting for the 'Mean stress effect'*** σ_{mean}

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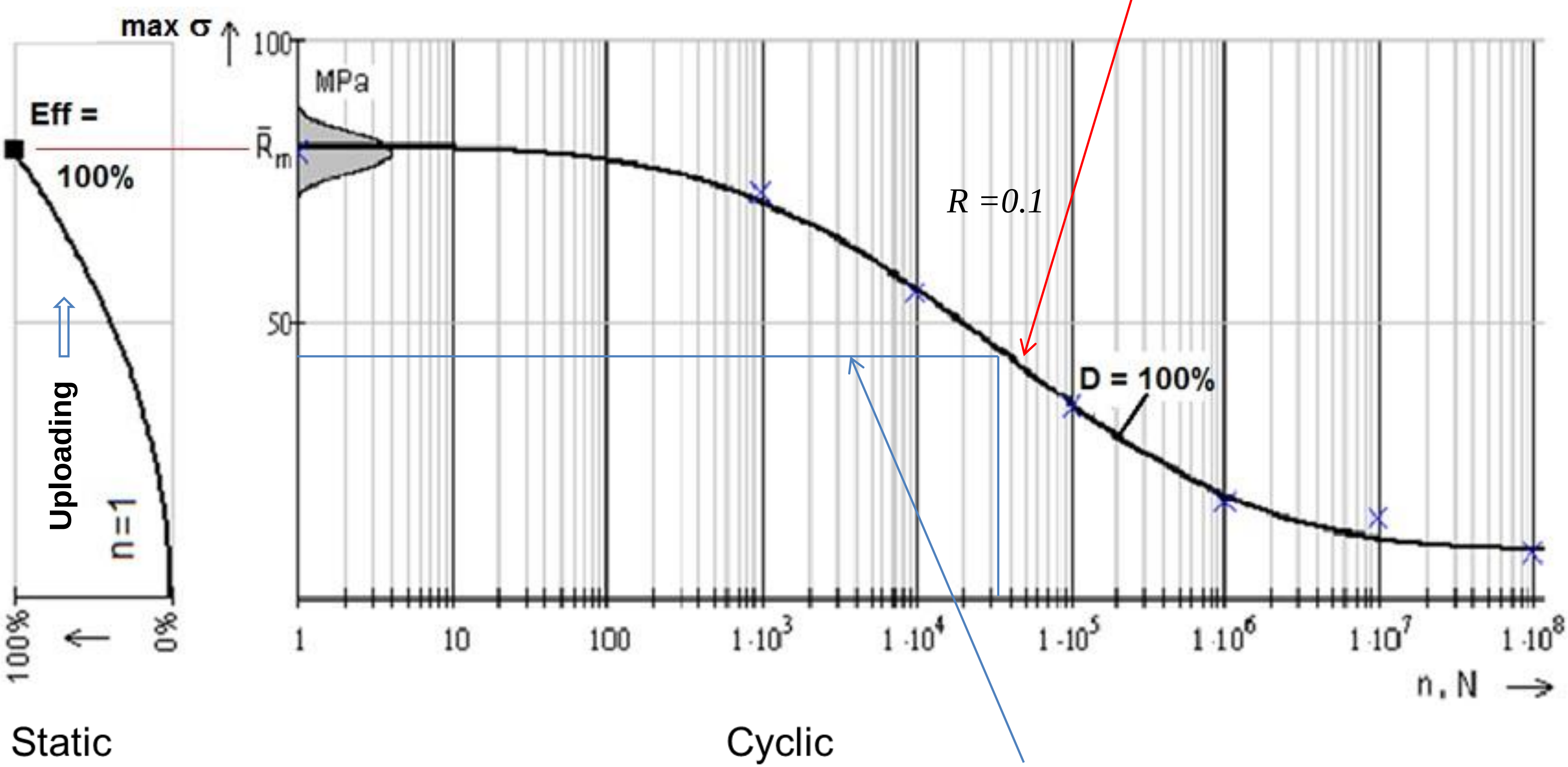
Static and cyclic development of damaging, S-N-curve



Static
R_m basic strength

Cyclic
residual strength $\sigma(R, N)$

Analogous limits of the material capacities :
- Static : material stressing effort Eff = 100 %
- Cyclic : material damaging sum D = 100 %

For brittle behaving materials it is advantageous to use $max\sigma \equiv R_m$ instead of $\Delta\boldsymbol{\sigma}$

Failure mode-linked Master S-N-curves

For lifetime estimation usually – even in a dictinct failure mode – several S-N-curves are needed

testing requires high effort!

<u>Idea</u>

Measurement of just one failure mode linked Master S-N-curve

- for a fixed stress ratio *R*
- prediction of additionally necessary S-N-curves on basis of the master curve and on the 'principle of equivalent strain energy'!

Then, for the often used

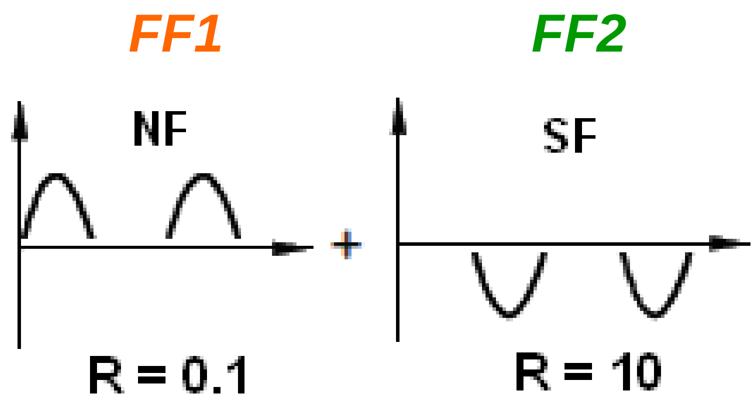
all possible load orientations capturing fiber-dominatedly designed, multidirectional laminates, composed of UD plies,

an engineering-like model is derivable.

S := cyclic stress range $\Delta\sigma$, N := number of cycles to failure, stress ratio R := $min\sigma / max\sigma$

Application of Miner-'Rule'

Mode-wise Accumulation of Damaging Portions (novel)



Simple Example: again

R = -1

$$D\ (FF1, FF2) = NF:(n_1 / N_1 + n_2 / N_2 + n_3 / N_3) + SF:(n_4 / N_4)$$

$$+ \quad D\ (IFF1, IFF2, IFF3) \ = \ D \leq \ D_{feasible}$$

from test experience

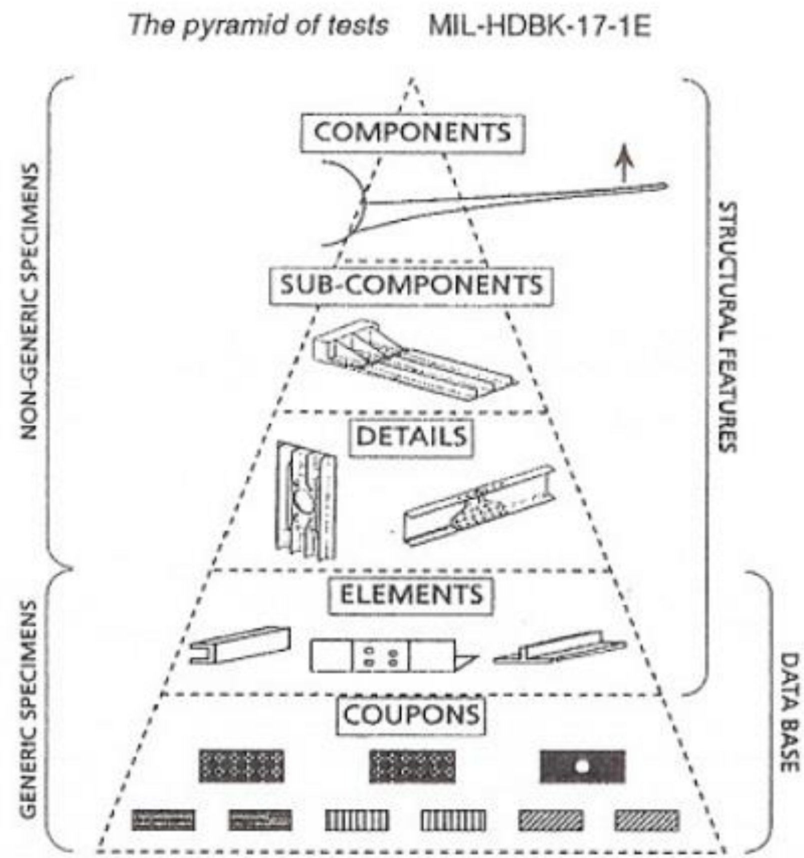
Calulation, see [Cun13b]

Short Presentation of CCeV + personal activities

1. **Structural Development, Design Requirements, and Design Verifications**
2. **Dimensioning Load cases, Safety Concept and Design Factors of Safety**
3. **Modelling of Composites (elasticity, strength)**
4. **Material Strength Failure Conditions (SFC)**
5. **Application of SFCs to Some Materials**
6. **Lifetime Prediction**
7. **Material Properties**
8. **Model Parameters**
9. **Standardized Material Test Methods** **Kollege**
10. **Structural Testing, NDI, Damage Tolerance**
11. **Structural Verification, Margin of Safety, Reserve Factor**

Characterisation of Composite Material and Components

MIL Hdbk 17: *Composites*	Material			Structure
Structural complexity level	*Screening*	*Qualification*	*Acceptance*	*structural substantiation*
constituent	X			
lamina	X	X	X	
laminate		X	X	X
structural element	X	X	X	X
structural compon.				X



composite test specimens

Modelling & Discretizing determines type of test specimen

FE-Programme: Konstrukteure haben Schwierigkeiten beim Einsetzen der richtigen Werkstoffkennwerte !!

Gottfried Wilhelm Leibniz (about 1800)

A general system
of signs and symbols is of
high importance for
a logically consistent universal language
for scientific use !

Self-explaining Notations for Strength Properties (homogenised material) neu !!!!

		Fracture Strength Properties									required by material symmetry
	loading	**tension**			**compression**			**shear**			
	direction or **plane**	1	2	3	1	2	3	12	23	13	
9	**general orthotropic**	R_1^t	R_2^t	R_3^t	R_1^c	R_2^c	R_3^c	R_{12}	R_{23}	R_{13}	**comments**
5	**UD, ≅ non-crimp fabrics**	$R_{\parallel}^{t}$ NF	$R_{\perp}^{t}$ NF	$R_{\perp}^{t}$ NF	$R_{\parallel}^{c}$ SF	$R_{\perp}^{c}$ SF	$R_{\perp}^{c}$ SF	$R_{\parallel\perp}$ SF	$R_{\perp\perp}$ NF	$R_{\parallel\perp}$ SF	$R_{\perp\perp} = R_{\perp}^{t} / \sqrt{2}$ (compare Puck's modelling)
6	**fabrics**	R_W^t	R_F^t	R_3^t	R_W^c	R_F^c	R_3^c	R_{WF}	R_{F3}	R_{W3}	*Warp = Fill*
9	**fabrics general**	R_W^t	R_F^t	R_3^t	R_W^c	R_F^c	R_3^c	R_{WF}	R_{F3}	R_{W3}	*Warp ≠ Fill*
5	**mat**	R_{1M}^t	R_{1M}^t	R_{3M}^t	R_M^c	R_{1M}^c	R_{3M}^c	R_M^τ	R_M^τ	R_M^τ	$R_M^\tau(R_M^t)$
2	**isotropic**	R_m SF	R_m SF	R_m SF	*deformation-limited*			R_M^τ	R_M^τ	R_M^τ	*ductile, dense* $R_M^\tau = R_m / \sqrt{2}$
		R_m NF	R_m NF	R_m NF	R_m^c SF	R_m^c SF	R_m^c SF	R_m^σ NF	R_m^σ NF	R_m^σ NF	*brittle, dense* $R_M^\sigma = R_m^t / \sqrt{2}$

NOTE: *As a consequence to isotropic materials (European standardisation) the letter R has to be used for strength. US notations for UD material with letters X (direction 1) and Y (direction 2) confuse with the structure axes' descriptions X and Y . *Effect of curing-based residual stresses and environment dependent on hygro-thermal stresses. *Effect of the difference of stress-strain curves of e.g. the usually isolated UD test specimen and the embedded (redundancy) UD laminae. R_m := 'resistance maximale' (French) = tensile fracture strength (superscript t here usually skipped), R:= basic strength. Composites are most often brittle and dense, not porous! SF = shear fracture

Elasticity Properties ***(homogenised material)*** *(self-explaining denotations)*

considers VDI 2014,

proposed to ESA-Hdbk

		Elasticity Properties									
	direction or plane	1	2	3	12	23	13	12	23	13	
9	***general orthotropic***	E_1	E_2	E_3	G_{12}	G_{23}	G_{13}	ν_{12}	ν_{23}	ν_{13}	**comments**
5	***UD, ≅ non-crimp fabrics***	$E_{\|\|}$	$E_{\perp}$	$E_{\perp}$	$G_{\|\|\perp}$	$G_{\perp\perp}$	$G_{\|\|\perp}$	$\nu_{\|\|\perp}$	$\nu_{\perp\perp}$	$\nu_{\|\|\perp}$	$G_{\perp\perp} = E_{\perp} /(2+2\nu_{\perp\perp})$ $\nu_{\perp\|\|} = \nu_{\|\|\perp} \cdot E_{\perp} / E_{\|\|}$ *quasi-isotropic 2-3-plane*
6	***fabrics***	E_W	E_F	E_3	G_{WF}	G_{W3}	$G_{\|W3}$	ν_{WF}	ν_{W3}	ν_{W3}	*Warp = Fill*
9	***fabrics general***	E_W	E_F	E_3	G_{WF}	G_{W3}	G_{F3}	ν_{WF}	ν_{F3}	ν_{W3}	*Warp ≠ Fill*
5	***mat***	E_M	E_M	E_3	G_M	G_{M3}	G_{M3}	ν_M	ν_{M3}	ν_{M3}	$G_M = E_M/(2+2\nu_M)$ *1 is perpendicular to quasi-isotropic mat plane*
2	***isotropic*** *for comparison*	*E*	*E*	*E*	*G*	*G*	*G*	*v*	*v*	*v*	*G=E /(2+2v)*

Lesson Learned: - *Unique, self-explaining denotations are mandatory*
- *Otherwise, expensively generated test data cannot be interpreted and go lost*

Hygrothermal Properties *(homogenised material)*

		Hygro-thermal properties					
	direction	1	2	3	1	2	3
9	general orthotropic	α_{T1}	α_{T2}	α_{T3}	α_{M1}	α_{M2}	α_{M3}
5	UD, ≅ non-crimp fabrics	$\alpha_{T\|\|}$	$\alpha_{T\perp}$	$\alpha_{T\perp}$	$\alpha_{M\|\|}$	$\alpha_{M\perp}$	$\alpha_{M\perp}$
6	fabrics	α_{TW}	α_{TW}	α_{T3}	α_{MW}	α_{MW}	α_{M3}
9	fabrics general	α_{TW}	α_{TF}	α_{T3}	α_{MW}	α_{MF}	α_{M3}
5	mat	α_{TM}	α_{TM}	α_{TM3}	α_{MM}	α_{MM}	α_{MM3}
2	isotropic for comparison	α_{T}	α_{T}	α_{T}	α_{M}	α_{M}	α_{M}

.. analogous for λ, c

material friction μ as strength property

NOTE: Despite of annoying some people, I propose to rethink the use of α for the CTE and β for the CME.
Utilizing α_T and α_M automatically indicates that the computation procedure will be similar.

Key Words: Material properties, CFRP, T300, Code69, UD-Prepreg

References

[1] Report QE-630 / 83, WEP, DORNIER, 1978/79

[2] Report DOL73/74, DORNIER, 1973/74

[3] Report SK50-266/85, DORNIER, 1985

1 Material

Material specification	CFRP T300 / Code69 UD-Prepreg
Specification for delivery	DOL 74, Edition January 1978

Characteristic	Unit	Value (remarks)
Fiber type		Toray T300/6K
Fiber density	g/cm^3	1.75
Matrix type		Epoxy-Code69
Matrix density	g/cm^3	1.27
Prepreg ply thickness	mm	0.231
Contents of prepreg resin	mass %	43±2.5
Fiber volume fraction	%	60
Prepreg density	g/cm^3	1.56
Cure process specification		DOL 74, Edition January 1978
Cure temperature	°C	175 (hold time = 75 min.)
Cure vacuum	bar	0.07 (hold time = whole process)
Cure pressure	bar	7 (hold time = whole process)
Post cure temperature	°C	

2 Physical properties

Characteristic	Unit	Value	Statistics	Ref.
c	kJ/(K · kg)			
$\lambda_{\parallel}$	W/(K · m)			
$\lambda_{\perp}$	W/(K · m)			
$\kappa_{\parallel}$	1/(Ω · m)			
$\kappa_{\perp}$	1/(Ω · m)			

3 Mechanical properties

Test temperature		RT		
Moisture contents		SA[a]		
Property	Unit	Value	Statistics	Ref.
$R_{\parallel t}$	MPa	1280	A	[1]
$R_{\perp t}$	MPa			
$R_{\parallel c}$	MPa			
$R_{\perp c}$	MPa			
$R_{\perp\parallel}$	MPa			
$ILSS$	MPa	65	A	[1]
$E_{\parallel t}$	MPa	133000/116000	$\overline{x}$/A	[1]
$E_{\perp t}$	MPa			
$E_{\parallel c}$	MPa			
$E_{\perp c}$	MPa			
$G_{\parallel\perp}$	MPa			
$\nu_{\parallel\perp}{}^{c}$	-	0.32	$\overline{x}$	[2]
$\nu_{\perp\perp}$	-	0.4^{d}		
$e_{\parallel t}$	%	1.3	S	[2]
$e_{\perp t}$	%			
$e_{\parallel c}$	%			
$e_{\perp c}$	%			
$e_{\parallel\perp}$	%			
$\alpha_{M\parallel}$	mm/(mm · %)			
$\alpha_{M\perp}$	mm/(mm · %)			
$\alpha_{T\parallel}$	mm/(mm · K)	$-(0.8 \pm 0.2) \cdot 10^{-6}$	$\overline{x}$	[2]
$\alpha_{T\perp}$	mm/(mm · K)	$+(27.0 \pm 1.0) \cdot 10^{-6}$	$\overline{x}$	[2]
T_g	°C	200	[b]	[3]

T_g = glass transition temperature

[a] = Standard Atmosphere according to ISO554/DIN50014: $23/50 = 23 \pm 2°C/50 \pm 5\%RH$

[b] = no statistical base

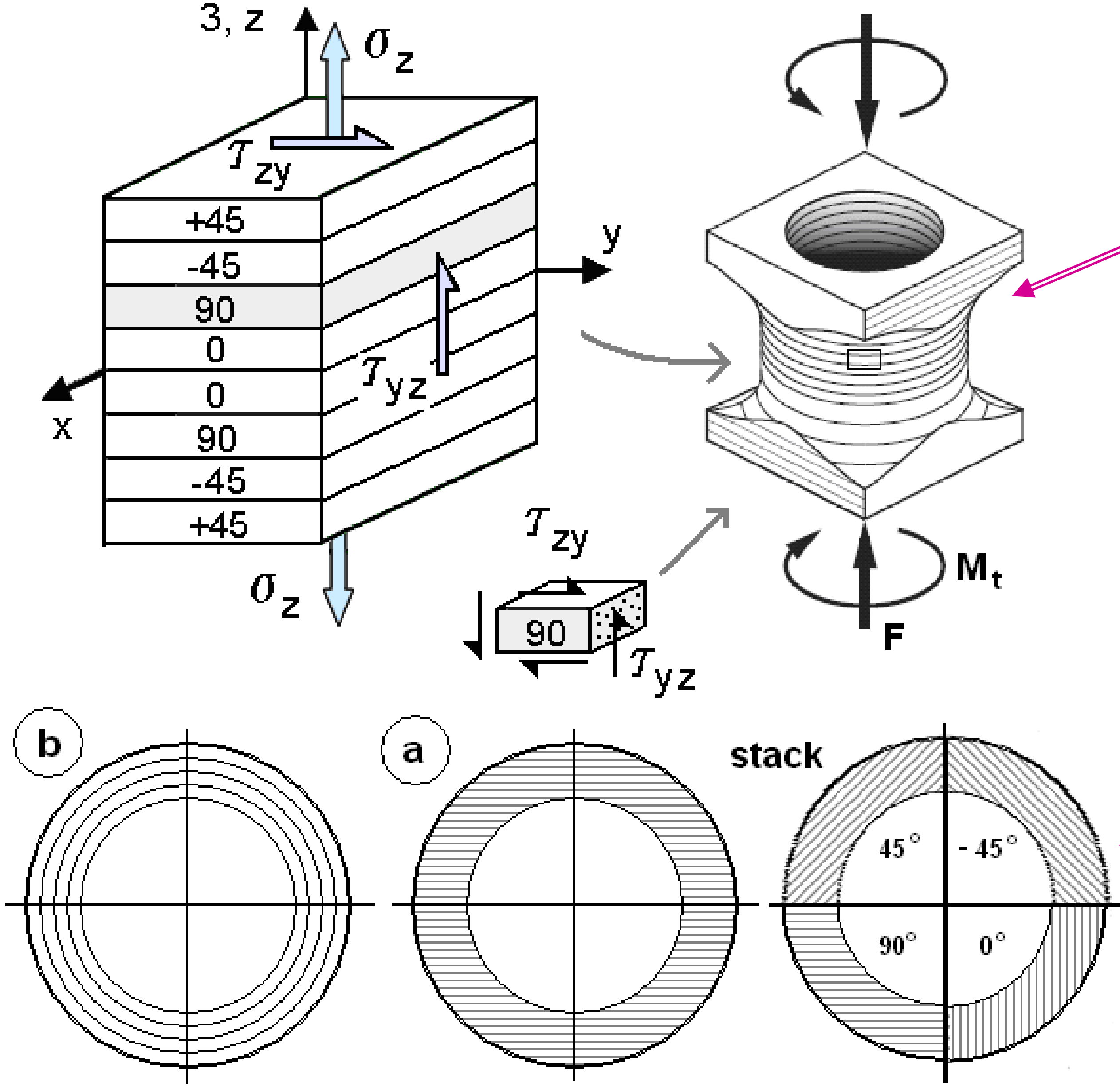
[c] = major value

[d] = assumed

Note: DOL 74 (Edition Jan.78) has been replaced by DOL 74 (Edition Nov.82), strength data have not changed. Determination of the elastic moduli according to LN 29971.

Beispiel: HSB-Werkstoffblätter

Test Case 10, Test Specimen, WWFE-II,
Test domain around the critical material location must be smooth!



tube milled from
a laminate block

Lesson Learnt: Not usable for the validation of a SFC !

no smooth stress domain for validating failure conditions

edge effects etc.

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UD lamina (ply) : Micro-mechanical Properties

Some lamina analyses require a micro-mechanical input:

Problem: Not all micro-mechanical properties can be measured.

Solution: Micro-mechanical equations are calibrated by macro-mechanical test results (lamina level) = an *inversal parameter identification*

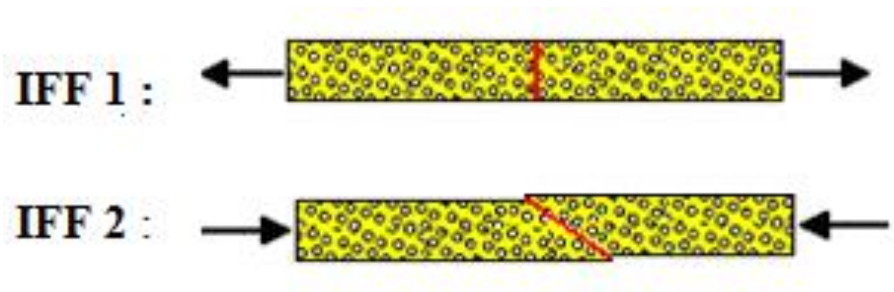
Condition: micro-mechanical properties can be used <u>only</u> together with the equations they have been determined with.

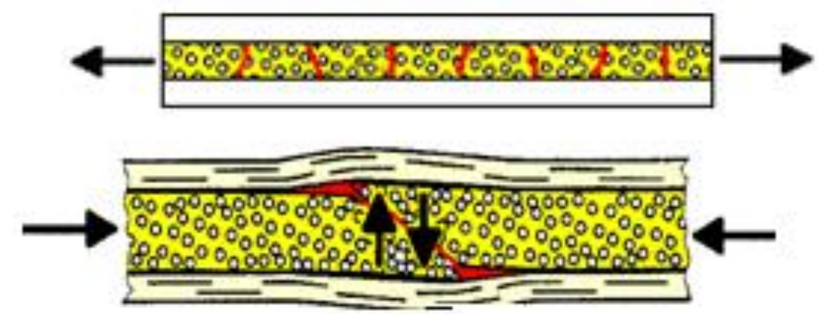
Mind the difference in UD-analysis : Isolated and embedded UD-behaviour

‘Isolated‘ lamina test specimens
= weakest link results (series failure system)

‘Embedded‘ laminas experience in-situ effects
= redundancy result (parallel failure system)

Measurement/Determination of strain softening curve ?





unconstrained lamina

delivers strength property, stress-strain curve

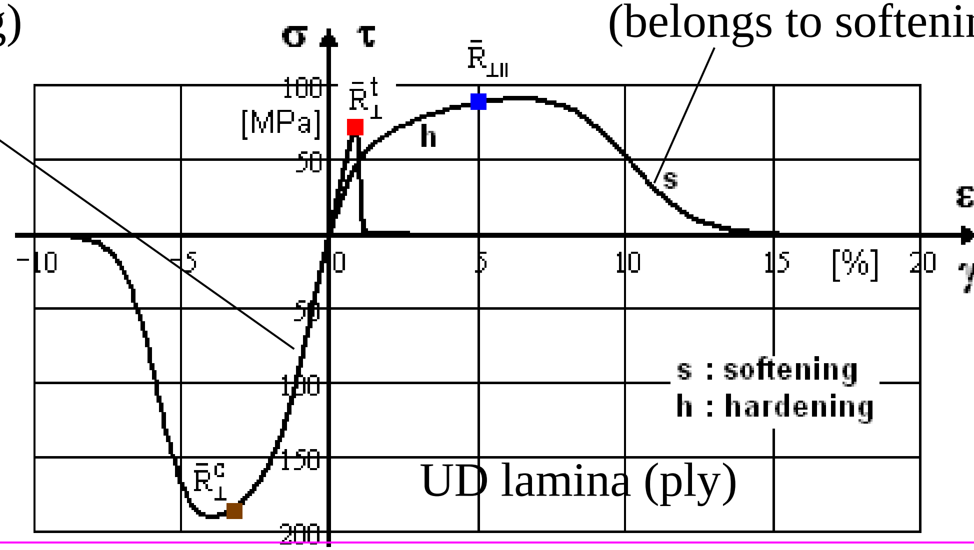
(belongs to hardening)

delivers basic strength
as analysis input !

mutually constrained laminas, in laminates

in <u>non-linear</u> laminate analysis

(belongs to softening)



<u>Lesson Learned</u>: *In the Post-IFF regime the embedded lamina experiences no sudden death but still has residual strength and stiffness due to in-situ effect!*

Determination of the 2 Friction Parameters (Mohr-Coulomb relationship)

(brittle behaviour)

IFF 3 :

$$\tau_{21} = R_{\perp\|} - b_{\perp\|} \cdot \sigma_2$$ *: FMC corresponds*

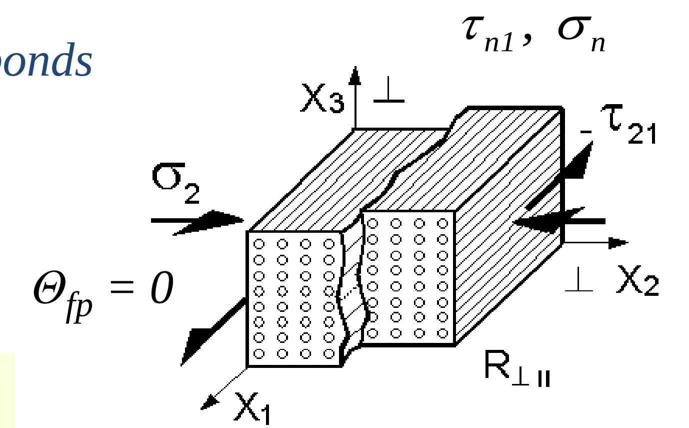
$$\tau_{n1} = R_{\tau}^{\perp||} - \mu_{\perp||} \cdot \sigma_n$$ *: Mohr*

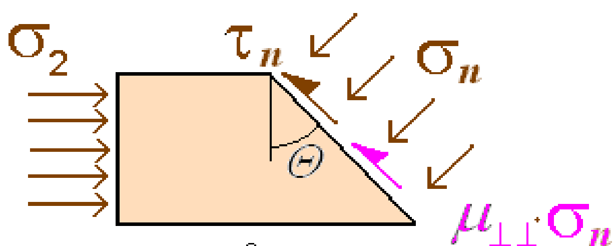
cohesion strength — *material internal friction coefficient*

***Linear* Mohr-Coulomb approach + denotation**

IFF 2 :

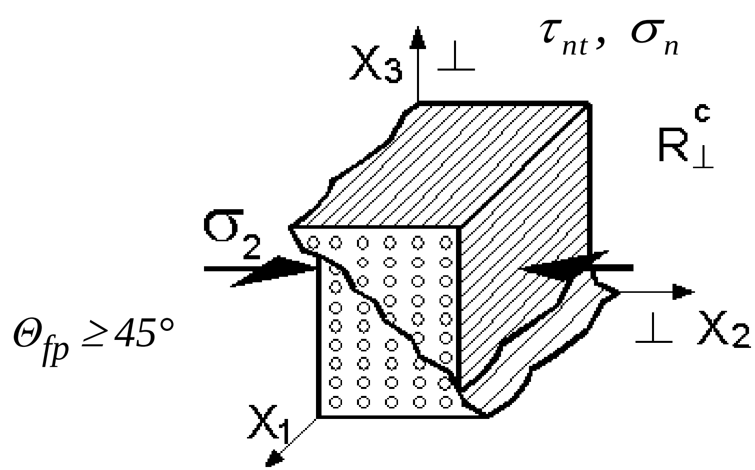
$$\tau_{nt} = R_{\tau}^{\perp\perp} - \mu_{\perp\perp} \cdot \sigma_n$$





$$\sigma_n = \cos^2\Theta \cdot \sigma_2$$

$$\tau_n = -\sin\Theta \cdot \cos\Theta \cdot \sigma_2$$



UD material: 2 ; isotropic material: 1

real material = crystal + friction

Determination of the Friction Parameter $\mu_{\perp\perp}$ (linear Mohr-Coulomb relationship)

From evaluation of the test data:

$$\theta_{fp}^{c} = 55°,\ R_{\perp}^{c} = 104\ MPa$$

FMC:

$$b_{\perp}^{\tau}\sqrt{I_4} = \bar{R}_{\perp}^{c} - (b_{\perp}^{\tau} - 1)I_2$$

$$b_{\perp}^{\tau} = \frac{1}{1+(\cos 2\Theta_{fp}^{c})} = \frac{1}{1-\mu_{\perp\perp}}$$

$$b_{\perp}^{\tau} = 1.52$$

Mohr-Coulomb:

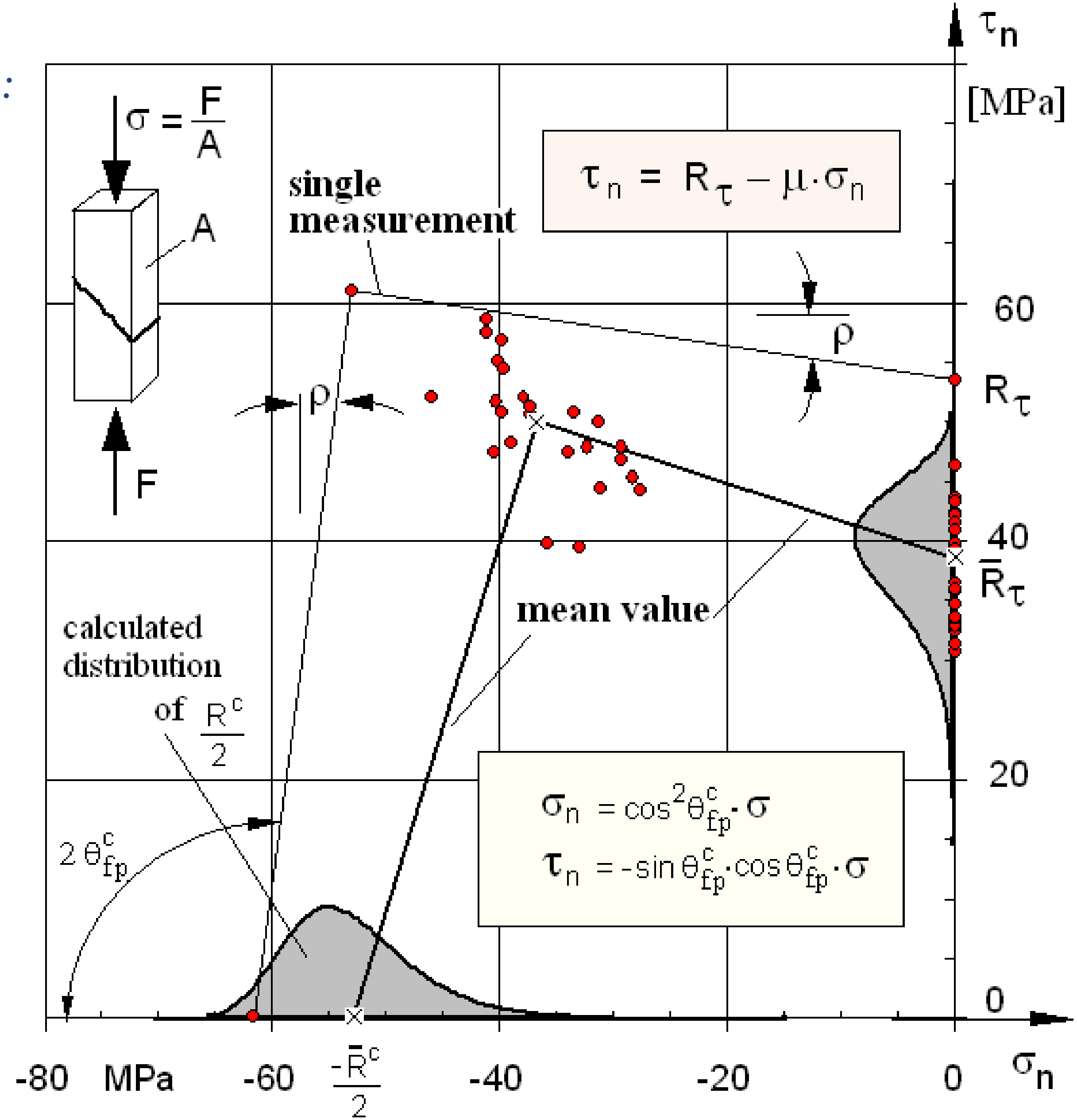
$$\tau_n = (R_{\tau}^{\perp\perp} - \mu_{\perp\perp}\cdot\sigma_n)$$

$$\mu_{\perp\perp} \geq -\cos 2\Theta_{fp}^{c},$$

$$\mu_{\perp\perp} = 0.34$$

$$R_{\tau}^{\perp\perp} = R_{\perp}^{c}\frac{1+\cos 2\Theta_{fp}^{c}}{2}$$

$$R_{\tau}^{\perp\perp} = 36.4\ MPa$$



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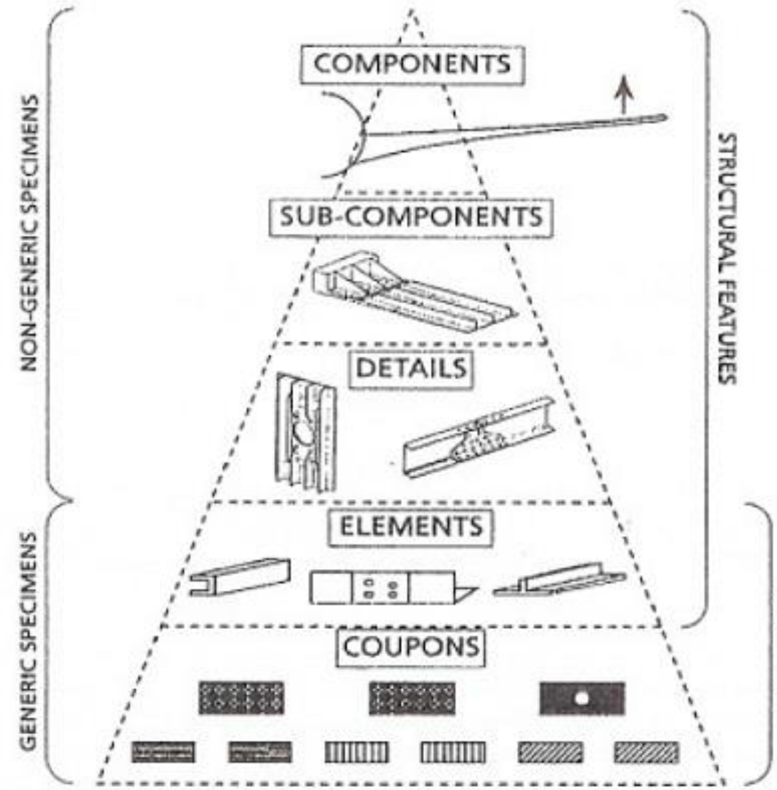
MIL Hdbk 17: *Composites*	Material			Structure
Structural complexity level	***Screening***	***Qualification***	***Acceptance***	***structural substantiation***
constituent	X			
lamina	X	X	X	
laminate		X	X	X
structural element	X	X	X	X
structural compon.				X

The pyramid of tests MIL-HDBK-17-1E



composite test specimens

Modelling & Discretizing
determines type
of test specimen

Test Standards Used

Wyoming Test Fixtures, ..
information.

SECTION A: SHEAR LOADING

A-1 Iosipescu Shear (ASTM D 5379)
A-2 V-Notched Rail Shear (ASTM D 7078)
A-3 Short Beam Shear (ASTM D 2344)
A-4 Two-Rail Shear (ASTM D 4255)
A-5 Three-Rail Shear (ASTM D 4255)
A-6 Shear Strength by Punch Tool (ASTM D 732)
A-7 Sandwich Panel Flatwise Shear (ASTM C 273)
A-8 Special Sandwich Panel Shear Fixture (ASTM C 273)

SECTION B: COMPRESSION LOADING

B-1 Wyoming Combined Loading Compression (ASTM D 6641)
B-2 Modified ASTM D 695 (Boeing BSS 7260)
B-3 IITRI Compression (ASTM D 3410)
B-4 Wyoming Modified IITRI
B-5 Wyoming Modified Celanese
B-6 Celanese (formerly ASTM D 3410)
B-7 German Modified Celanese (DIN 65 380)
B-8 Edgewise Compressive Strength (ASTM C 364)
B-9 NASA Short Block Compression
B-10 Lockheed F-22 Test Fixtures
B-11 Compression Subpress (ASTM D 695)
B-12 Compression Platens - Fixed and Spherical Seat

SECTION C: SPECIALTY COMPRESSION TEST FIXTURES

C-1 Boeing Open-Hole Compression (ASTM D 6484)
C-2 Northrop Open-Hole Compression (NAI-1504C)
C-3 Boeing Compression After Impact (ASTM D 7137)
C-4 NASA Compression After Impact (NASA 1092)

SECTION D: FLEXURAL LOADING Back to Top

D-1 Three & Four Point Flexure (ASTM D 790,D 6272 and D 7264)
D-2 Long Beam Flexure (C 393)
D-3 Fixed-Span Long Beam Flexure (C 393)
D-4 Ceramic Flexural Strength (ASTM C 1161)
D-5 Ceramic Equibiaxial Flexural Strength (ASTM C 1499)

SECTION E: TENSILE LOADING Back to Top

E-1 Standard Tensile Wedge Grips
E-2 Simple Tensile Wedge Grips
E-3 Tensile Wedge Grip Inserts
E-4 Specialized Tensile Testing Grips
E-5 Line Grips for Thin Sheeting
E-6 Split Capstan Grips
E-7 Briquet Tensile Grips
E-8 Split Collar Grips
E-9 Adhesive Bond Tensile Grips
E-10 Universal Joints
E-11 Adapters, Lock Rings, Pins

SECTION F: SPECIALTY TENSILE TESTS Back to Top

F-1 Sandwich Panel Flatwise Tensile - 2" Blocks (ASTM C 297)
F-2 Sandwich Panel Flatwise Tensile - 1" Blocks (ASTM C 297)
F-3 Curved Beam Strength (ASTM D 6415)
F-4 Split Disk Tensile (ASTM D 2290)

SECTION G: FRACTURE TOUGHNESS TESTS Back to Top

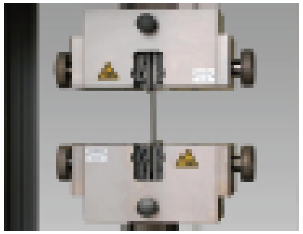
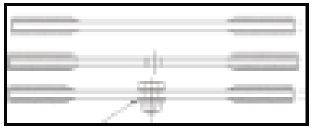
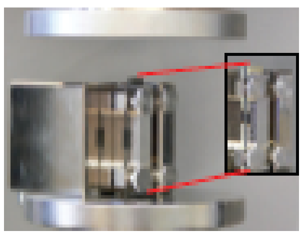
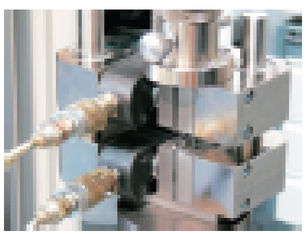
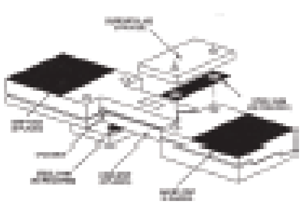
G-1 Mixed Mode Bending (ASTM D 6671)
G-2 Tensile Clevises (ASTM E 399)

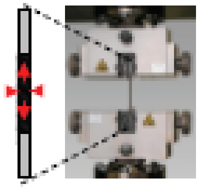
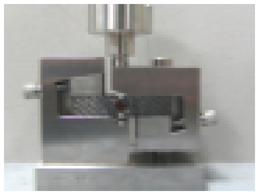
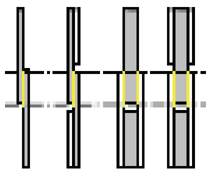
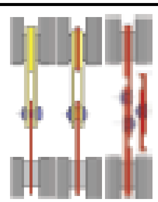
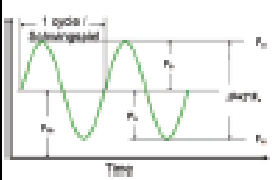
SECTION H: FASTENER RELATED TESTS Back to Top

H-1 Fastener Bearing Specimen Support (ASTM D 5961)
H-2 Laminate Bearing Strength – SACMA
H-3 Laminate Bearing Strength – ASTM D 5961
H-4 Plastic Bearing Strength – ASTM D 953
H-5 Fastener Double Shear (MIL-STD-1312-13)
H-6 Three-Plate Shear (Fed. Test 406, Method 1041)
H-7 Fastener Pull-Thru Strength (MIL-STD-1312-8A)\

SECTION I: BOND TESTS Back to Top

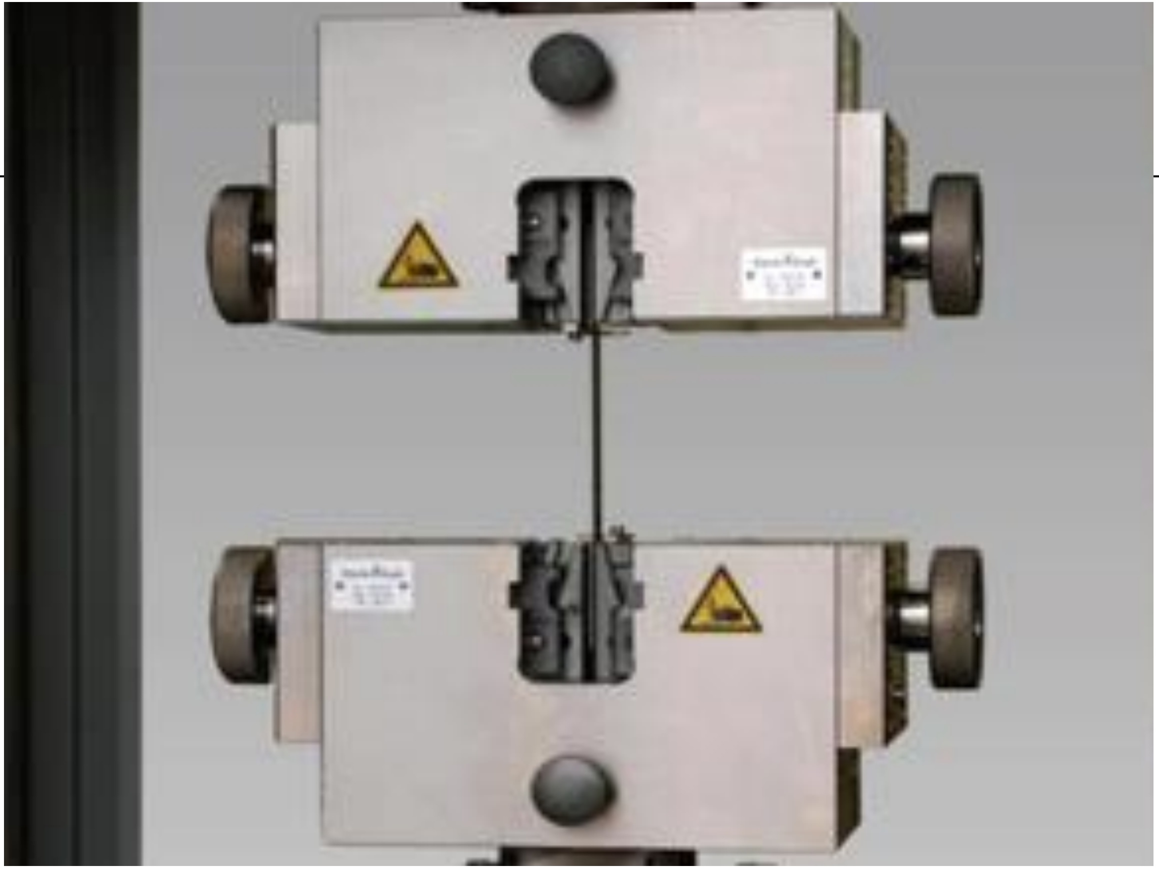
I-1 Climbing Drum Peel (ASTM D 1781)
I-2 Roller Drum Peel (ASTM D 3167)
I-3 NASA 90-Degree Peel
I-4 Block-Shear of Adhesive Bonds (ASTM D 4501)
I-5 Lapped Block Shear of Adhesive Bonds (ASTM D 905)
I-6 Weld Shear (ASTM A 497 & A 185)

Prinzip	Prüfart	Normenbeispiele	Aussage
	**Zugversuch**	ASTM D 3039, EN 2561, EN 2597, ISO 527 Teil 4 und Teil 5, DIN 675378, Airbus AITM 1-0007, Boeing BSS 7320, SACMA SRM 4 und SRM 9 Für Filamentstränge: ASTM D 4018, ASTM D 3916, ISO 11566	Zugeigenschaften wie Zugmodul, Zugfestigkeit und Bruchdehnung, Poissonsche Zahl an flachen Probekörpern, Messungen an Filamentsträngen. Bei unidirektionalen Laminaten auch längs und quer zur Faserrichtung.
	**Kerbzugversuch (open hole / bolted hole)**	ASTM D 5766, ASTM D 6742, prEN 6035, Airbus AITM 1.0007	Beurteilung des Schädigungsmerkmals.
	**Druckversuch mit stirnseitiger Krafteinleitung (end loading)**	ASTM D 695 (modifiziert), prEN 2850, ISO 14126, AITM 1-0008, Boeing BSS 7260 - type III and IV	Druckmodul, Druckfestigkeit, Druckstauchung, Versagensart.
	**Druckversuch mit flachseitiger Krafteinleitung (Shear loading / combined loading)**	ASTM D 3410, ASTM D 6641, prEN 2850, ISO 14126, Airbus AITM 1-0008	Druckmodul, Druckfestigkeit, Druckstauchung, Versagensart Bei dieser Prüfmethodik werden die Spannungskonzentrationen an den Probenenden vermieden und die Führung des Probekörpers ist besser als bei
	**Kerbdruckversuch (open hole / bolted hole)**	ASTM D 6484, ASTM D 6742, prEN 6036, Airbus AITM 1-0008, Boeing BSS 7260 - Type 1	Beurteilung des Schädigungsmerkmals.
	**Interlaminarer Scherversuch, Kurzbiegemethode**	ISO 14130, ASTM D 2344, EN 2377, EN 2563	Scheinbare interlaminare Scherfestigkeit. Bei dieser Prüfmethode wirken starke Flächenpressungen an der

	**Schubversuch in Lagenebene (± 45° Schubversuch)**	ISO 14129, prEN 6031, ASTM D 3518, AITM 1-0002, DIN 65466	Schubmodul, Schubspannungen und -festigkeiten, Schubverformung
	**V-Kerb Schubversuch (Iosipescu)**	ASTM D 5379	Schubmodul, Schubspannungen und -festigkeiten, Schubverformung.
	**Scherung in Lagenebene**	EN 2243-1, EN 2243-6, prEN 6060, AITM 1-0019, DIN 65148, ASTM D 3914	Scherfestigkeit und Schubverformung zwischen den Lagen. Diese Prüfung wird auch bei Verklebungen angewandt.
	**Dreipunkt und Vierpunkt Biegeversuch**	EN 2562, EN 2746, ASTM D 7264, ASTM D 790, ISO 14125, ASTM D 6272	Biegeeigenschaften wie Biegemodul, Biegespannungen und Biegefestigkeit
	**Lochleibung**	ASTM D 5961, ASTM D 7248, Airbus AITM 1.0009, prEN 6037, DIN 65562	Charakterisierung einer Bolzen-, Niet-, oder Schraubverbindung hinsichtlich Tragfähigkeit und Lochleibung.
	**Dynamisch zyklische Beanspruchung**	ISO 13003, ASTM D 3479, ASTM D 6873	Charakterisierung der Materialermüdung, Lebensdauer, Versagensart.
	**Compression After Impact (CAI)**	ISO 18352, prEN 6038, ASTM D 7137, DIN 65561, AITM 1-0010, Boeing BSS 7260 - type II	Beurteilung der Schädigung einer Prüfplatte anhand des Druckfestigkeitsverlustes. Die Schädigung wird durch eine definierte schlagförmige Beanspruchung üblicherweise mit einem instrumentierten Fallwerk

Test Standards Used

Tensile Test



Zugeigenschaften wie Zugmodul, Zugfestigkeit und Bruchdehnung, Poissonsche Zahl an flachen Probekörpern, Messungen an Filamentsträngen. Bei unidirektionalen Laminaten auch längs und quer zur Faserrichtung.

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Short Presentation of CCeV + personal activities

1. **Structural Development, Design Requirements, and Design Verifications**
2. **Dimensioning Load cases, Safety Concept and Design Factors of Safety**
3. **Modelling of Composites (elasticity, strength)**
4. **Material Strength Failure Conditions (SFC)**
5. **Application of SFCs to Some Materials**
6. **Lifetime Prediction**
7. **Material Properties**
8. **Model Parameters**
9. **Standardized Material Test Methods**
10. **Structural Testing, NDI, Damage Tolerance**
11. **Structural Verification, Reserve Factor**

Material & Structural Testing and NDI

Materials Testing

Structural Testing (most often destructive testing)

Non-Destructive Testing (NDT, NDI, NDE),

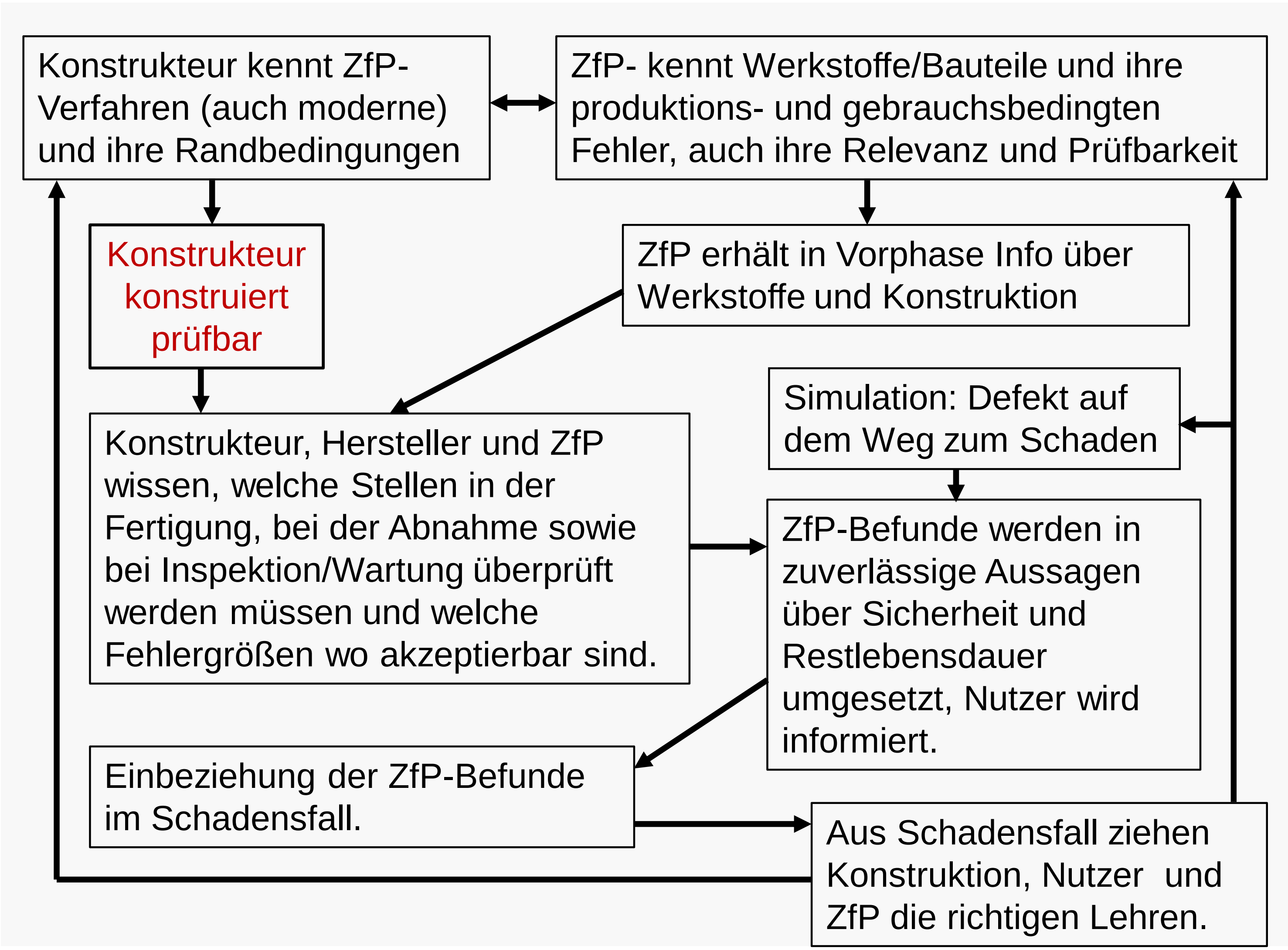
NDI should be part of a
"systems solution"

* Failure: Detection, localization, sizing + shaping

* Failure: Assessment (*risk-based)*

Non-Destructive Testing (Zerstörungs-freie Prüfung)

Gerd Busse: Wunschtraum über Einbindung der ZfP



Structural Testing (often destructive testing)

Structural Testing

(often destructive testing)

ARIANE 5

Front Skirt

Lesson Learnt:

Strain gages in the smooth strain regimes , only !

Structural Testing of GROWIAN

Damage Threat Assessment for Composite Structure

FAR 25.571 Damage Tolerance & Fatigue Evaluation of Structure … must show that catastrophic failure due to fatigue, corrosion, *manufacturing defects, or accidental damage* will be avoided through the operational life of the airplane.

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10. Structural Testing, NDI, Damage Tolerance
11. Structural Verification, Reserve Factor

Design Verification = Achievement of a Reserve against a Limit State

For each distinct Load Case with its single Failure Modes must be computed:

<u>R</u>eserve <u>F</u>actor (is load-defined) **:** ***RF = Failure Load / applied Design Load***

Material Reserve Factor : f_{Res} **= *Strength / Applied Stress***

if linear analysis: $f_{Res} = RF = 1 / Eff$

Material Stressing Effort : ***Eff = 100% if RF = 1*** **(Anstrengung)**

(Werkstoff-Anstrengung)

is applicable in linear and non-linear analysis.

Conclusions w.r.t. Failure Mode Concept – derived Strength Failure Conditions

- **The FMC is an efficient concept** = may be vieded as **'Anisotropic Mises'**

  that improves prediction + simplifies design verification

  is applicable to brittle and ductile, dense and porous, isotropic, transversely-isotropic and orthotropic materials

  if clear failure modes can be identified and if the material element can be homogenized.

  Formulation basis is whether the material element experiences **a *volume* change, a *shape change* and *friction* .**

  Builds not on the ***material*** but on ***material behaviour !***

- **Delivers a combined formulation of *independent modal failure modes*,**

  without the well-known drawbacks of global SFC formulations

  (which *mathematically combine in-dependent failure modes)* .

- **The FMC-based Failure Conditions are simple but describe physics of each single failure mechanism pretty well.**

- **Mapping of a brittle behaving isotropic porous foam and of a transversely-isotropic UD material was successful, thereby validating the SFC models.**

Some Literature

[Cun96] Cuntze R.: *Bruchtypbezogene Auswertung mehrachsiger Bruchtestdaten und Anwendung im Festigkeitsnachweis sowie daraus ableitbare Schwingfestigkeits- und Bruchmechanikaspekte*. DGLR-Kongreß 1996, Dresden. Tagungsband 3

[Cun04] Cuntze R.: *The Predictive Capability of Failure Mode Concept-based Strength Criteria for Multidirectional Laminates*. WWFE-I, Part B, Comp. Science and Technology 64 (2004), 487-516

[Cun05] Cuntze R.: *Is a costly Re-design really justified if slightly negative margins are encountered?* Konstruktion, März 2005, 77-82 and April 2005, 93-98 (reliability treatment of the problem)

[Cun12] Cuntze R.: *The predictive capability of Failure Mode Concept-based Strength Conditions for Laminates composed of UD Laminas under Static Tri-axial Stress States. - Part A of the WWFE-II*. Journal of Composite Materials 46 (2012), 2563-2594

[Cun13] Cuntze R.: *Comparison between Experimental and Theoretical Results using Cuntze's 'Failure Mode Concept' model for Composites under Triaxial Loadings - Part B of the WWFE-II*. Journal of Composite Materials, Vol.47 (2013), 893-924

[Cun13b] Cuntze R.: *Fatigue of endless fiber-reinforced composites*. 40. Tagung DVM-Arbeitskreis Betriebsfestigkeit, Herzogenaurach 8. und 9. Oktober 2013, conference book

[Cun14] Cuntze R.: associated paper, see CCeV website http://www.carbon-composites.eu/leistungsspektrum/fachinformationen/fachinformation-2

[Cun15a] Cuntze, R.: *Static & Fatigue Failure of UD-Ply-laminated Parts – a personal view and more.* ESI Group, Composites Expert Seminar, Uni-Stuttgart, January 27-28, 201, keynote presentation, see CCeV website)

[Cun15b] Cuntze, R.: *Reliable Strength Design Verification – fundamentals, requirements and some hints.* 3rd. Int. Conf. on Buckling and Postbuckling Behaviour of Composite Laminated Shell Structures, DESICOS 2015, Braunschweig, March 26 -27, extended abstract , conf. handbook, 8 pages (see CCeV website)

[VDI2014] VDI 2014: German Guideline, Sheet 3 *"Development of Fiber-Reinforced Plastic Components, Analysis".* Beuth Verlag, 2006 (*in German and English, author was convenor).*